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Strategies for Improving Maintenance Efficiency and Reliability Through Wrench Time Optimization

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Abstract: This study investigates the optimization of wrench time to improve maintenance efficiency and reliability within a chemical processing plant. Wrench time, defined as the proportion of time spent directly performing maintenance tasks, was quantified through random observations of maintenance technicians. The findings revealed an average wrench time of 28% across the site, with variations between individual crew groups ranging from 20% to 35% and craft-specific wrench times varying from 13.3% to 45.5%. Several inefficiencies were identified, including prolonged wait times for equipment isolation, safety clearance, job planning, and parts procurement. Key contributing factors to these inefficiencies were found to include poor coordination between maintenance and production, insufficient work prioritization, inadequate adherence to schedules, a high volume of emergency tasks, and the absence of essential tools such as bills of materials (BOMs), equipment data, and troubleshooting checklists. To address these challenges, a range of improvement initiatives were implemented. These included enhancing coordination between maintenance and production by refining process steps, introducing additional planning tools for effective work prioritization, providing job aids, developing generic troubleshooting checklists, leveraging Industrial Internet of Things (IIoT) technologies, and establishing metrics to monitor progress. Early indications suggest that these initiatives have led to a reduction in maintenance backlog and gradual improvements in overall equipment effectiveness (OEE). It is anticipated that these changes will result in increased wrench time, enhanced maintenance quality and reliability, reduced downtime, and lower operational costs. For maintenance managers and engineers, the findings offer actionable insights into optimizing workflows and resource allocation, thereby contributing to the improvement of operational efficiency and reliability.

Keywords: Wrench time; Maintenance efficiency; Work prioritization; Integrated planning; Scheduling; Resource allocation

1 Introduction

Maintenance management is a critical component in ensuring the optimal performance and reliability of industrial systems. The role of maintenance has undergone a significant evolution, transcending its traditional confines as a support function within manufacturing organizations. Maintenance now occupies a pivotal position in ensuring the long-term sustainability of operations by increasing the availability, reliability, safety, and quality of production processes while concurrently mitigating adverse environmental impacts such as waste and emissions [1, 2]. Maintenance activities primarily influence the economic dimension of organizational sustainability and constitute a major portion of manufacturing costs. In manufacturing organizations, maintenance costs can range from approximately 15–40% of total operational expenses [3]. For thermal power plants and offshore wind farms, up to 30% of all electricity generation costs are attributable to maintenance [4, 5]. Therefore, the profitability and competitiveness of an organization depend on the effective implementation of maintenance strategies [4]. The proper implementation of maintenance significantly affects the downtime of the production line and the overall performance of the production system [6]. Although maintenance activities are crucial for enhancing the reliability of systems, improper execution can result in equipment failure and abnormal, excessive shutdowns of the production line [7]. Moreover, timely execution of maintenance activities improves performance and reduces equipment failure [8].

A significant aspect of maintenance efficiency is the effective utilization of technician labor, often measured through wrench time. Wrench time refers to the actual time technicians spend performing hands-on maintenance tasks, excluding preparatory work, administrative duties, travel, and other nonvalue-added activities. Despite its importance, wrench time in many organizations is often suboptimal, leading to increased downtime, higher operational costs, and reduced asset reliability.

Parida and Kumar [9] highlighted the challenges associated with maintenance system performance measurement and proposed a model to accurately link and estimate the contribution of maintenance to business goals. In industries where maintenance activities constitute a substantial portion of operational expenditures and where minimizing equipment downtime is crucial for productivity and profitability, improving wrench time can provide tremendous returns. Previous studies have shown that wrench time can vary widely, with many organizations achieving only 25–35% effective wrench time [10, 11], whereas the Society of Maintenance and Reliability Professionals (SMRP) [12] indicates best-in-class values as high as 50–55%. To achieve such high performance, it is essential to analyze the factors that contribute to nonproductive time, including planning processes, logistics, and organizational inefficiencies. Studies have highlighted common issues such as poor planning, inadequate materials, and excessive travel time [13, 14]. A recent case study conducted by Velasquez et al. [15] on the maintenance process in an underground copper mine in Chile identified 11 non-productive activities and their associated lost time and opportunity costs. These activities, including breaks due to emergencies, equipment waiting for washing, waiting for parts, and waiting for tools, were categorized as productivity losses. The total lost time was found to be 23,800 hours per year, with a corresponding cost of approximately $1.12 million per year due to non-production.

Site performance metrics, such as OEE, are traditionally linked to organizational or site objectives and goals. OEE combines availability, performance, and quality metrics to provide a comprehensive view of how effectively equipment is utilized. Within this framework, equipment availability is a function of the mean time between failures (MTBF) and the mean time to repair (MTTR). The MTTR is a primary maintenance efficiency metric. The MTTR measures how quickly equipment can be returned to service after a repair activity, and a lower value indicates a more efficient maintenance process. This directly correlates with greater wrench time, as more efficient repairs typically involve less nonvalue-added activity [11]. High wrench time means that maintenance technicians spend more time on actual maintenance tasks than on preparatory or ancillary activities. Improving the MTTR can significantly impact the overall equipment availability and thus enhance the OEE. By reducing the time needed to repair equipment, organizations can increase the availability and performance of their assets, leading to fewer disruptions in production and higher overall productivity. This improvement is closely tied to the optimization of maintenance processes, which includes better planning, scheduling, and execution of maintenance tasks.

However, MTTR is a lagging indicator; it reflects past performance rather than providing real-time insights into where maintenance processes may have bottlenecks, losses, or inefficiencies. This is where a wrench time study becomes invaluable. By studying the wrench time losses, organizations can identify inefficient processes and determine where to focus improvement efforts. For example, if significant time is lost waiting for parts or permits, this highlights areas where process adjustments or resource reallocations are needed.

To address these inefficiencies, targeted interventions can be proposed to increase wrench time. These include maintenance process optimization, better resource allocation, and the implementation of advanced maintenance technologies. Effective approaches include the widespread use of predictive maintenance (PdM) technologies, total productive maintenance (TPM), and lean maintenance practices. These methodologies have proven effective in similar contexts by enhancing the planning, scheduling, and execution of maintenance tasks [16–18]. By focusing on optimizing maintenance processes and incorporating advanced technologies, organizations can significantly improve their wrench time. This leads to enhanced productivity, better asset reliability, reduced operational costs, and ultimately, greater alignment of maintenance activities with business goals.

The centralized maintenance department in a chemical plant faces challenges such as delays and execution inefficiencies, which are evident from high equipment downtime. No previous survey has been conducted to establish a sitewide baseline on wrench time and associated losses. This investigation measured wrench time for maintenance activities in a chemical process plant, along with the various unproductive tasks that different maintenance crews perform daily.

The objective of this survey was twofold: first, to establish a baseline of current wrench time in maintenance operations through direct observation and data collection; second, to implement identified improvement opportunities based on the observed wrench time losses. By identifying and quantifying the time spent on these unproductive activities, several improvement initiatives were implemented to streamline processes and develop a sustained maintenance management system. Conducting a wrench time study is crucial because it addresses a fundamental aspect of maintenance management by identifying nonvalue-added tasks. An increased wrench time directly increases the efficiency and productivity of maintenance technicians, improves asset reliability, reduces downtime, and lowers maintenance costs. The findings of this study provide valuable insights for maintenance managers and engineers, enabling them to optimize their operations and achieve higher levels of efficiency and effectiveness. By focusing on wrench time, organizations can uncover inefficiencies, prioritize improvements, and ultimately enhance their overall maintenance performance.

2 Estimation Methods and Benefits of Wrench Time

Wrench time is a primary indicator of the effectiveness of the planning and scheduling aspects of the work management process. Recently, Chatterjee and De [19] proposed wrench time as a key performance indicator (KPI) to measure maintenance productivity. Their study, which was conducted in central engineering maintenance, demonstrated improvements in wrench time and maintenance productivity through dedicated maintenance planning, scheduling, and a systematic study of other performance indicators based on data generated from enterprise resource planning (ERP) software. Similarly, Rizlan et al. [20] separated value-added maintenance tasks from nonvalue-added tasks to identify improvement opportunities. This stratification revealed that the real value-added time was only 20.4%, prompting the development of an action plan to eliminate existing nonvalue-added tasks. Their initiatives included visual control for tooling, the establishment of an effective preventive maintenance (PM) schedule, and the implementation of effectiveness meetings at the beginning of each shift. By focusing on wrench time as a KPI and differentiating between value-added and nonvalue-added tasks, organizations can uncover significant areas for improvement in maintenance operations. This approach not only enhances the productivity of maintenance but also ensures more efficient use of resources, leading to better asset reliability and reduced operational costs.

2.1 Estimation Methods

The SMRP [12] recommends measuring wrench time either by directly tracking the time spent on different work categories or by sampling the number of observed work categories. However, determining the actual time spent on each activity can be cumbersome. One approach involves each maintenance technician wearing an electronic device that generates a signal or beep at fixed intervals. The technicians then either record their activity on an electronic device or write it down on a card, from which the wrench time percentage can be calculated. This method, known as self-reported wrench time, has its downsides. It can be prone to overestimation due to perceived biases involved in the process. Technicians may unintentionally or intentionally report more productive time than actually spent, leading to inaccurate wrench time data. Such discrepancies can hinder the identification of genuine inefficiencies and the implementation of effective improvement initiatives.

A statistical sampling process where each technician has an equal chance of being observed over a sufficient period to represent the actual workforce over time is considered the best method and was adopted for the current study. It is presumed that the percentage of observations is equivalent to the percentage of time. The survey included sampling random technician personnel from the beginning of the day shift to the end while they were involved in various activities and assigned an activity category every 15 minutes. A similar method of wrench time study was demonstrated by Palmar [21].

The following formula was used for wrench time estimation:

$$\text{Wrench Time } (\%) = \frac{\text{Wrench Time Observations}}{\text{Total Observations}} \times 100 \tag{1}$$

The percentage of wrench time is a key indicator of how effectively maintenance resources are being utilized. Higher wrench time percentages generally correlate with more efficient maintenance processes, as technicians spend more time on productive tasks and less time on nonvalue-added activities. Conversely, low wrench time indicates potential issues such as poor planning, inadequate resource allocation, or inefficiencies in work execution.

2.2 Benefits

Typically, maintenance is viewed as a necessary evil that only incurs expenses; however, recent studies have highlighted that an efficient maintenance process can provide significant benefits to an organization's bottom line by increasing production volume. A case study conducted by Alsyouf [22] at a Swedish papermill showed that a paper mill machine could ideally generate an additional profit of $0.975 million per year, with 12.5% of its annual maintenance budget by avoiding all unplanned stoppages and poor-quality production due to maintenance-related causes.

Maximizing wrench time has a direct effect on plant productivity and performance. When maintenance personnel spend more time on value-added tasks and can service equipment efficiently, the corresponding equipment downtime is reduced, and maintenance backlog is minimized. This leads to improved equipment availability, OEE, higher operational reliability, and, ultimately, better overall plant performance. Figure 1 illustrates how increased wrench time can contribute to the improvement in OEE by decreasing the MTTR and downtime and thereby improving equipment availability. The improvement in OEE can be used to justify the investment in wrench time improvement initiatives.

Additionally, a small increase in wrench time can generate significant soft savings for the organization. For example, annual savings from increased wrench time by only 5% can be estimated by multiplying $100 per hour for a technician as loaded in the computerized maintenance management system (CMMS):

8 hrs./technician/shift × 5 shifts/week × 52 weeks × $100/hr./technician × 50 technicians × 5% = $520,000/year

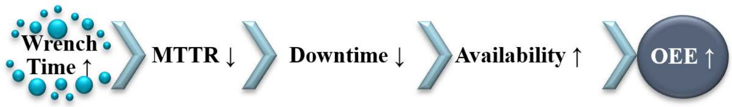

Figure 1. Impact of wrench time improvement on OEE

Increasing labor efficiency could yield financial gains of over half a million dollars for the plant. However, increasing wrench time is not intended for a reduction in maintenance resources, rather than achieving more efficiency of the maintenance department and productivity. By optimizing maintenance processes and improving wrench time, the plant can experience significant cost savings in maintenance and operational improvements, leading to more efficient and reliable production. An increased wrench time also contributes to the effective implementation of proactive maintenance strategies, such as PM and PdM, further increasing plant reliability.

3 Assessment and Results of Wrench Time Study

3.1 Work Management Process

Understanding the current work management process and the steps a work order goes through during its life cycle is crucial. This knowledge allows the identification of inefficiencies and areas for improvement, ensuring that maintenance activities are effectively planned, scheduled, and executed. The chemical plant has developed a structured maintenance work management system and achieved maintenance management maturity using a CMMS over time.

Once a maintenance service request is entered in the CMMS, the maintenance gatekeeper reviews the request for accurate problem description, equipment number, and priority and approves notification by converting it to a work order. The work order is then routed to the planner's backlog for further processing. The planner defines the scope, identifies the required materials and components, estimates labor hours, and procures the necessary items. Once planning is complete, the work order is moved to the "ready to schedule" backlog. The planner conducts a weekly schedule preparation meeting every Thursday, and a weekly schedule is published on Fridays, outlining the list of work orders planned for the following week. Additionally, a daily work coordination meeting is held by the maintenance supervisor and gatekeeper to review already completed work orders, the status of the ongoing works and jobs scheduled for the next business day.

A copy of the work order and associated information is provided to the technician by the maintenance supervisor to ensure that they have the necessary details to conduct the work. The maintenance supervisor reviews the scope of the work with the technician, if needed. The parts and materials for the job are sourced either from preplanned kits or from stores. Next, the technician collaborates with the gatekeeper or production supervisor to complete the Task Analysis Safety Card (TASC), which must be finalized before any work can begin. During the TASC review, all hazards and risks are assessed collectively by the technicians and operations personnel. Appropriate actions for isolating the equipment or system, such as tagging and locking, are performed collaboratively before commencing the work. For nonroutine tasks, the technician obtains a safety clearance from the site safety coordinator. Upon completion of the work, the technician first informs the production area supervisor, followed by the maintenance supervisor. The system or equipment is not returned to service until the technician and the production supervisor have removed all isolation devices in accordance with safety procedures.

3.2 Maintenance Activity Categorizations

The centralized maintenance department of the chemical plant consists of four crews or work centers, each comprising a varying number of trade personnel and classifications, as shown in Tables 1 and 2. All crews and trade classifications participated in the wrench time study. Prior to conducting the field survey, each crew member was informed about the objectives and methodology of the study to prevent confusion. The survey involved random sampling of technicians in an unbiased manner, focusing solely on wrench time without assessing the quality of work or workmanship. Several improvement opportunities, such as enhanced coordination in work order planning, scheduling, and execution, were identified, implemented, and discussed in later sections of this study.

Palmer [23] provided 23 categories to capture all observed maintenance activities during a wrench time study. After consulting with the maintenance supervisor and maintenance manager, an activity category was selected, and various shift activities that fall under this category were identified for the current investigation. A total of 17 work categories were selected in sufficient detail to capture the entire shift activities of a technician from beginning to end. The crew members were sampled for the activity categories shown in Table 3. This classification helps simplify the survey and capture a wide range of activities involved in day-to-day maintenance activities in complex industrial settings. It also provides a means to conduct the survey objectively.

Table 1. Number of trades by crew

Crew	No. of Trades
Mechanical -1	20
Mechanical -2	11
Electrical & instrumentation	15
Facility maintenance	4
Total	50

Table 2. Trade classification

Trade Classification
Millwright
Fitters/welders
Sheet metal worker
Insulators
Electricians & instrument technicians
Carpenters
Auto mechanics
HVAC technicians

Table 3. Wrench time activity categories with examples

No.	Activity Category	Activity Example
1	Wrench time	Actual work on equipment
2	Planning	Clarification on work order, discussion with operator, reviewing drawing, and following troubleshooting procedure, etc.
3	Waiting for assignment	Waiting to receive assignment and instructions from supervisor
4	Waiting on process	Physical isolation, lockout/tagout (LOTO), shutdown, cooled down, draining, cleaning, etc.
5	Permit & clearance	TASC card signoffs and isolation list from production
6	Interference	Critical lifting, excavation, safety concerns at nearby job locations, and production activities around job or due to other reasons
7	Wrap-up activity	Work area and tool cleanup, paperwork, sign-off, and scanning for radiation
8	Pre- and post-work preparation	Wash up, shower, decontamination, and changing coveralls, etc.
9	Looking for tools and PPE	Carrying tools, PPE, respirators, and breathing apparatus, etc., to and from job site
10	Looking for parts & material	Looking for parts in stores, carrying parts to and from the job sites
11	Travel	Commuting to and from the job site
12	Meeting	Toolbox, safety meeting, etc.
13	Training	Computer-based, classroom, and on-the-job training, etc.
14	Idle	Not in break time, extended lunch, or break time, etc.
15	Work environment	Radiation, heat stress, extreme cold, health & safety concerns, etc.
16	Lack of skills & knowledge	New technician, and new to the site, etc.
17	Reassignment	Emergency work, change in priority, and reassignment, etc.

3.3 Sensitivity Analysis

The number of observations calculated is used to validate the initial wrench time estimate. In this study, an initial wrench time of 28% was used, and to ensure that this estimate was reliable, the calculated number of observations was used. This provides confidence that the observed wrench time is accurate and can be used to make informed decisions for improving maintenance processes.

When planning to measure wrench time, it is essential to determine the number of observations required to achieve a specific margin of error (MOE) with a certain confidence level. This ensures that the sample size is statistically significant and that the results can be generalized to the entire population of maintenance activities.

The formula for estimating the MOE is as follows:

$$MOE = Z\sqrt{\frac{p \cdot (1-p)}{n}} \tag{2}$$

To determine the sample size required to achieve a specific MOE with a given confidence level, the MOE formula can be rearranged as follows:

$$n = \frac{Z^2 \cdot p \cdot (1-p)}{MOE^2} \tag{3}$$

where, Z score corresponds to the desired confidence level (e.g., 1.96 for 95% confidence); p is the proportion (wrench time); and n is the sample size (number of observations).

It is expected to be 95% confident that the observed wrench time of 28% is within an MOE of 5%; these values can be plugged into Eq. (3) to give n = 309.73. Therefore, approximately 310 observations would be required to achieve an MOE of 5% with 95% confidence. In this study, 320 maintenance activities were sampled. If more activity observations, such as double the number (e.g., 640), were recorded, the MOE would not decrease significantly. It decreases from approximately 4.9% with 320 observations to only a smaller percentage, 3.5% with 640 observations. This diminishing return illustrates that many activity observations are needed to achieve a very narrow MOE, as shown in Figure 2.

A 95% confidence interval is widely accepted in scientific research, as it provides a high degree of certainty that the true population parameter (wrench time) lies within the specified MOE. In this study, sampling 320 observations ensures an MOE of 4.9%, which is considered sufficiently accurate for operational decision-making and site benchmarking. The 95% confidence level offers an optimal trade-off between sample size and statistical reliability, ensuring accurate results without excessively increasing the effort or time needed for data collection. This balance ensures that the sample size is both statistically significant and practical, providing reliable insights that can be confidently used to drive maintenance process improvements. Table 4 shows the MOE analysis for wrench time.

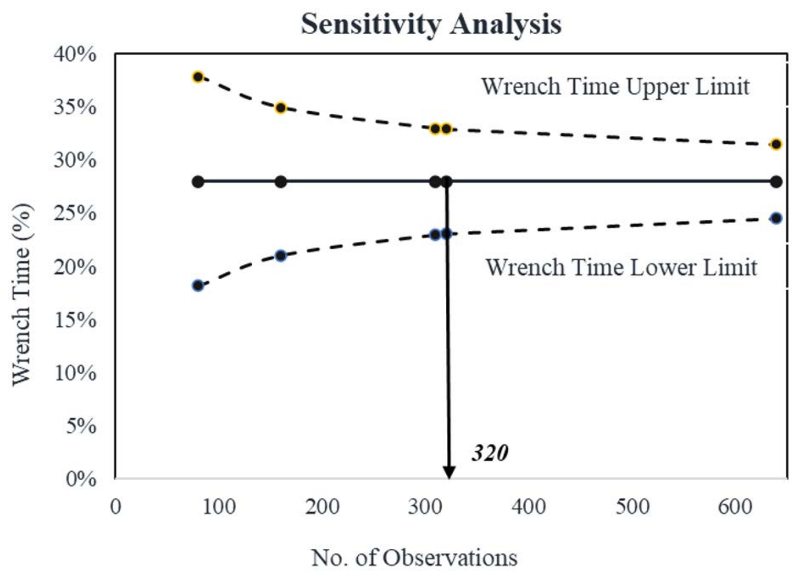

Figure 2. MOE analysis for wrench time, 28% with upper and lower limit boundaries

Table 4. MOE analysis for wrench time

WT = Sample Proportion, p	No. of Observation, n	MOE with 95% C.I	Wrench Time Upper Limit	Wrench Time Lower Limit
28%	80	9.8%	37.8%	18.2%
28%	160	7.0%	35.0%	21.0%
28%	**310**	**5.0%**	**33.0%**	**23.0%**
28%	**320**	**4.9%**	**32.9%**	**23.1%**
28%	640	3.5%	31.5%	24.5%

3.4 Pitfalls and Mitigation in Wrench Time Observations

The following outlines common pitfalls that could impact wrench time observation and the precautions taken to avoid these errors:

• Unconscious bias: Technicians may have an unconscious bias due to the awareness of being observed, potentially altering their behavior either by speeding up their work or overemphasizing productivity. To avoid this, technicians were instructed and coached to perform their regular duties without any perceived notion of needing to show higher productivity or concern over negative consequences due to lower productivity. By emphasizing that the purpose was to observe normal work processes, the potential for such bias was minimized, helping to ensure that wrench time data accurately reflected typical work conditions.

• Maintenance task selection: If the tasks sampled are not representative of the full range of maintenance activities, the study may overemphasize or overlook certain tasks, leading to skewed data. For example, PM/PdM jobs typically have higher wrench time than reactive or emergency tasks, and wrench time during plant shutdowns may differ significantly from normal operations. To mitigate this, the sampling was designed to capture a broad spectrum of tasks across the plant during normal operations. Random sampling was used to include various task types, such as PM, PdM, emergency repairs, and rebuilding work. The sampling was also stratified based on task type, criticality, and other relevant factors to ensure comprehensive coverage of maintenance activities.

• Scheduled sampling scheme: A scheduled sampling approach may not fully capture the variability of wrench time over time, as certain shifts or times of day may have more or less wrench time due to external factors like production schedule, maintenance workload or available resources. To address this, data was collected across different times of the day, days of the week, and shifts to account for all periods of the workday. Additionally, the study spanned three months to reduce variability due to specific periods, shifts, or seasonal factors. This approach ensured that potential variations in wrench time, driven by time-of-day, shift-based, or seasonality influences, were properly accounted for.

• Underrepresentation of certain crews or technicians: If the sample inadvertently underrepresents certain crews or technicians, the study's findings may not accurately reflect wrench time distribution across all maintenance teams, and inefficiencies specific to certain crews or trades may remain unrecognized. To prevent this, crews from various shifts and areas of the plant were included to ensure a diverse and representative sample. Technicians with at least six months of on-site experience were selected to ensure they had encountered a variety of scenarios and were familiar with site regulations. This selection strategy focused on capturing the full spectrum of maintenance activities, rather than strictly adhering to the number of technicians in each crew. This approach provided a well-rounded perspective on the maintenance process, helped reveal inefficiencies across different groups, and ensured the results were representative of the entire workforce.

• Not categorizing maintenance activities in sufficient detail: If the activities performed by technicians during their shifts are not sufficiently stratified, the sampling may miss key activities, and the results could fail to identify critical inefficiencies. To avoid this, all maintenance activities were stratified into detailed categories based on task types, shifts, and other relevant factors, as discussed in Section 3.2. This ensured that the sampling captured the full range of technician activities, minimizing bias and ensuring comprehensive representation of the factors that influence wrench time.

By addressing these potential pitfalls and adopting these corrective measures, the wrench time study provided reliable, representative results that are crucial for identifying inefficiencies and implementing effective maintenance process improvements.

3.5 Results

Table 5 presents a comprehensive overview of the survey findings related to wrench time and loss activity categories. This table breaks down the assessment results across various dimensions, including crew group, to offer a nuanced understanding of the observed inefficiencies. By disaggregating the data in this manner, the survey allows for a detailed examination of how different crew groups and trades contribute to overall wrench time losses. This structured analysis helps to pinpoint specific areas where gaps exist and where improvements can be made. For instance, it identifies which crew groups experience the most significant delays or inefficiencies, enabling targeted interventions. Figure 3 illustrates overall site wrench time along with different loss categories.

Figures 4–7 illustrate the percentages of different activities, in which the four crews were involved during the wrench time survey.

While the wrench time for mechanical crew 1 is as low as 20%, the highest wrench time is observed for the facility maintenance crew at 35%, with an overall site wrench time averaging 28%. The most significant contributors to wrench time loss include waiting for isolated equipment, obtaining permits and clearances, searching for parts and tools, lacking troubleshooting guidelines, and engaging in wrap-up activities. Another major factor impacting wrench time is reassignment, which occurs in response to emergencies and is as high as 10% for the E&I crew.

Table 6 illustrates the wrench time by trade classification, revealing that certain trades, such as auto mechanics and carpenters, have greater wrench times. This is largely because these technicians can work in their respective shops without needing production equipment isolation, long wait times for clearances, or unproductive travel times. Conversely, trades such as fitters/welders and heating, ventilating, and air conditioning (HVAC) technicians require special permits (e.g., hot work and working at heights) and clearances from production or area representatives. This additional layer of requirements is reflected in their lower wrench times compared with the overall site average. This distinction underscores the impact of administrative and procedural delays on wrench time efficiency across different trades.

Bolaji and Adejuyigbe [24] also highlighted several factors that negatively impact maintenance programs, including the lack of proper evaluation and review, inadequate monitoring of maintenance performance, low levels of planning, poor execution, and the unavailability of necessary spare parts. These challenges often result in undesired equipment failures and production losses. In the present investigation, various wrench time losses were carefully analyzed, identifying several areas for improvement. This led to the implementation of targeted initiatives aimed at reducing these inefficiencies. The following section discusses these improvement initiatives in detail, outlining the strategies employed to increase wrench time, enhance maintenance productivity, and ultimately improve overall plant reliability and efficiency.

Table 5. Wrench time survey results for each crew by activity category

No.	**Activity Category**	**Crews**				**Total Observations**
		Mechanical Crew 1	**Mechanical Crew 2**	**Electrical and Instrument Crew**	**Facility Service Crew**	
1	Wrench time	18	32	16	22	89
2	Execution planning	4	16	6		26
3	Waiting for assignment		2		2	4
4	Waiting on process	24	4			27
5	Permit & clearance	12	6	14	4	36
6	Interference	2				2
7	Wrap-up activity		2	6	6	14
8	Pre- and post-work preparation	2	8	4	6	20
9	Looking for tools and PPE	18	4			22
10	Looking for parts & material	6	4	4		14
11	Travel		4		2	6
12	Meeting	4	8	2	6	20
13	Training		4			4
14	Idle	2	10		10	22
15	Work environment					
16	Lack of skills & knowledge					
17	Reassignment	4		6	4	14
	Total observations	96	104	58	62	320

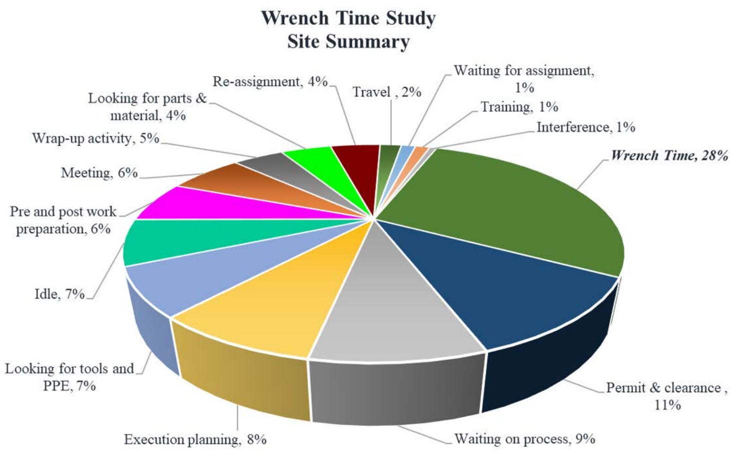

Figure 3. Overall site wrench time with different unproductive activities

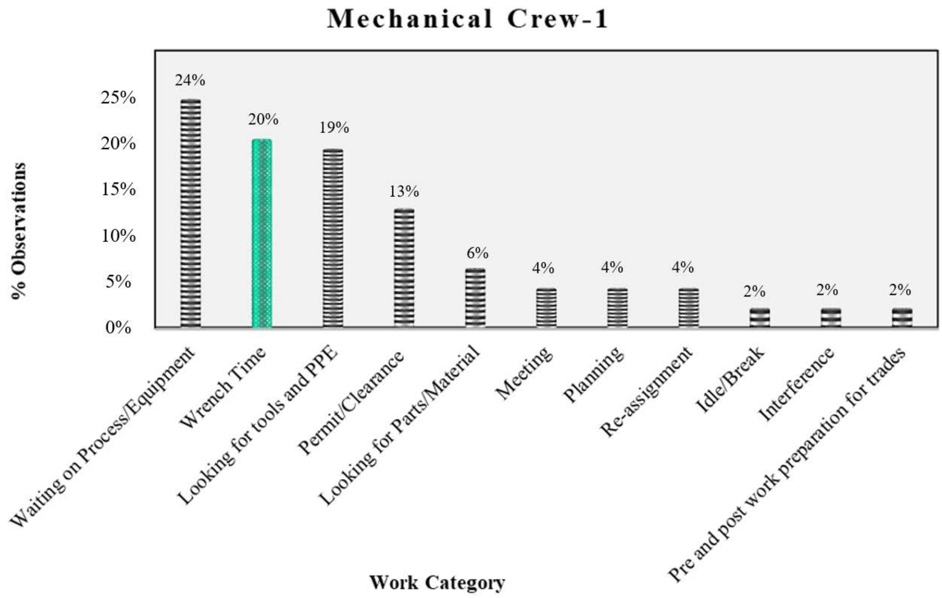

Figure 4. Wrench time and various unproductive activities of the mechanical crew 1

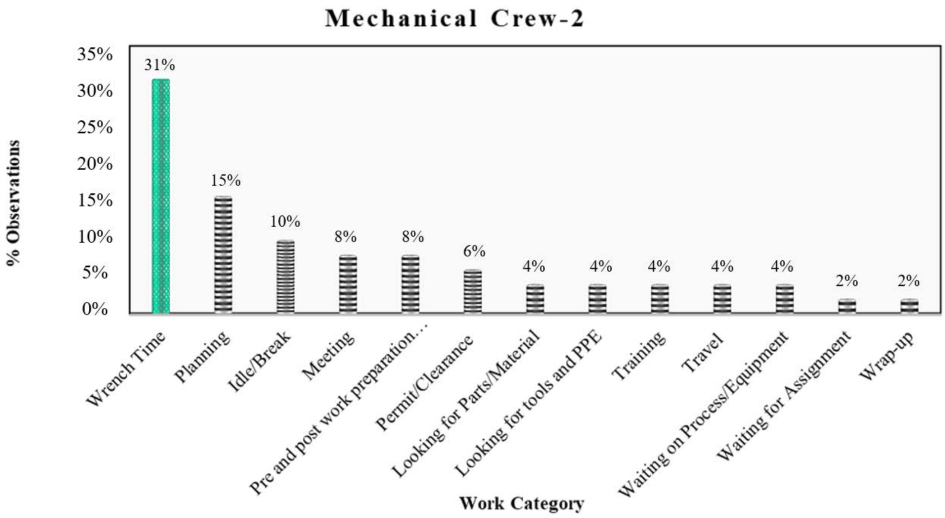

Figure 5. Wrench time and various unproductive activities of the mechanical crew 2

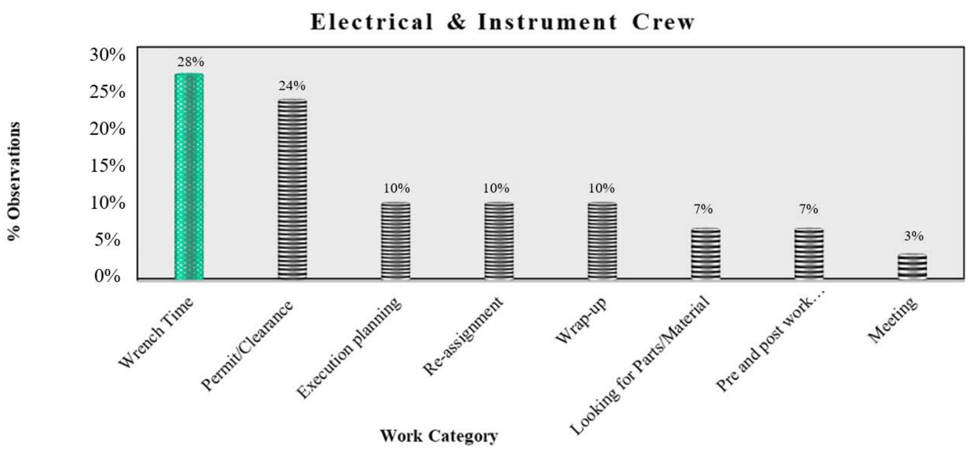

Figure 6. Wrench time and various unproductive activities for the electrical and instrument crew

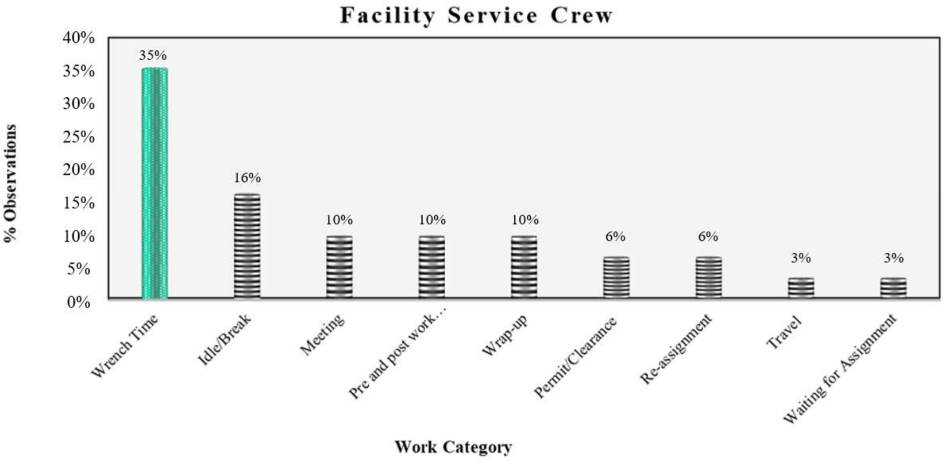

Figure 7. Wrench time and different unproductive activities for the facility service crew

Table 6. Observed wrench times for different trade classifications

Trade Classification	Wrench Time (%)
Auto mechanics	45.5%
Carpenters	40.0%
Sheet metal worker	28.6%
Millwright	28.4%
Electricians	27.6%
Insulators	22.2%
HVAC technicians	20.0%
Fitters/welders	13.3%

4 Sustainable Wrench Time Improvement

Achieving and sustaining optimal wrench time presents several challenges. Effective planning and scheduling are crucial, as they involve creating detailed work plans, ensuring the availability of necessary parts and tools, prioritizing tasks, and scheduling work to minimize downtime. However, delays in equipment isolation, unpredictability in parts procurement, and frequent emergency work can hinder smooth execution. Additionally, coordinating maintenance activities with production schedules is a significant challenge, as it requires close collaboration to ensure minimal disruption and optimal resource utilization. Aligning maintenance with production demands, such as scheduling during low-demand periods or shutdowns, can be complex, especially in high-paced environments. Furthermore, maintaining consistent communication between maintenance and production teams is essential for smooth execution but often proves difficult due to different priorities. Overcoming these challenges requires a coordinated, strategic approach to ensure continuous improvement in wrench time, maintenance quality and plant reliability.

4.1 Wrench Time Improvement Initiatives

Several improvement initiatives were considered to reduce various categories of wrench time losses observed across the plant. Importantly, due to the integrated nature of the maintenance work process, the explicit link between the implemented initiatives and specific wrench time loss categories may be obscure and difficult to distinctly comprehend, although each initiative is expected to positively impact multiple categories. For example, improving parts and materials management can reduce both the time spent searching for parts and the time spent traveling between the job site and the warehouse. Ensuring that parts and tools are pre-kitted and readily available at the job site minimizes delays and enhances overall efficiency. Similarly, enhancing communication between production and maintenance would expedite the permit and clearance processes, as well as reduce time spent waiting on processes.

Table 7 provides a comprehensive overview of the implemented initiatives, wrench time loss categories, and the corresponding percentage of wrench time losses, as found through the current study discussed in earlier sections, which are expected to be improved through these initiatives. By implementing these initiatives, the organization seeks to create a more efficient and responsive maintenance environment. Future wrench time studies will serve as benchmarks to measure the success of these initiatives and guide further improvements in maintenance processes.

Future wrench time study is anticipated to reflect the desired improvements in these loss categories, thereby validating the effectiveness of the initiatives. By continuously monitoring wrench time and other KPIs, organizations can identify areas for further improvement and ensure that the benefits of these initiatives are sustained over time. This ongoing focus on wrench time optimization can help organizations achieve higher levels of efficiency, reliability, and cost-effectiveness in their maintenance operations.

Table 7. Improvement initiatives and impacted wrench time loss categories

No.	Improvement Initiatives	Wrench Time Loss Categories & Current Loss %
1	Optimizing communication and coordination	Waiting on process (4)-8% Permit & clearance (5)-11%
2	Improving parts and material management	Looking for parts & material (10)-4% Travel (11)-2%
3	Implementing remote condition monitoring using IIoT	Execution planning (2)-8% Reassignment (17)-4%
4	Improving schedule adherence	Travel (11)-2% Reassignment (17)-4%
5	Job aids and tool management	Execution planning (2)-8% Looking for tools and PPE (9)-7%
6	Limiting emergency work orders	Execution planning (2)-8% Travel (11)-2% Reassignment (17)-4%

4.1.1 Optimizing communication and coordination

Research has shown that effective communication and coordination between maintenance and production teams are essential for improving operational efficiency and reducing unplanned downtime [25]. Integrated production and maintenance scheduling provides substantial benefits in resource-constrained situations, as highlighted by Geurtsen et al. [26]. By aligning production and maintenance priorities, wrench time loss categories, such as waiting times for permits and clearance and equipment availability, are expected to be reduced.

Safety is paramount at sites handling hazardous and toxic chemicals, necessitating extensive preparatory work before maintenance personnel can commence tasks. Observations indicate that maintenance personnel spend a significant portion of their morning obtaining permits, clearances, and securing physically isolated assets. There are instances where equipment is not received from the area owner at all. Maintenance crew 1 spends 38% of their shift time obtaining permits and isolated equipment, creating a substantial bottleneck. If the scheduled jobs cannot be executed due to equipment unavailability, technicians return to the maintenance shop for reassignment. After morning work assignments and safety meetings, supervisors often distribute multiple work orders to a technician, anticipating that at least one piece of equipment can be available, reflecting uncertainty in work execution.

Despite daily coordination meetings to align maintenance work with production priorities, gaps in communication and coordination persist. Enhancing communication between maintenance and production is essential for fostering a productive organization. In order to eliminate unproductive delays, production and maintenance have now committed to a two-week advanced locked schedule, as shown in Figure 8. The gatekeeper ensures all the necessary process isolations, LOTO, and special permits at the start of the day with the help of the production team.

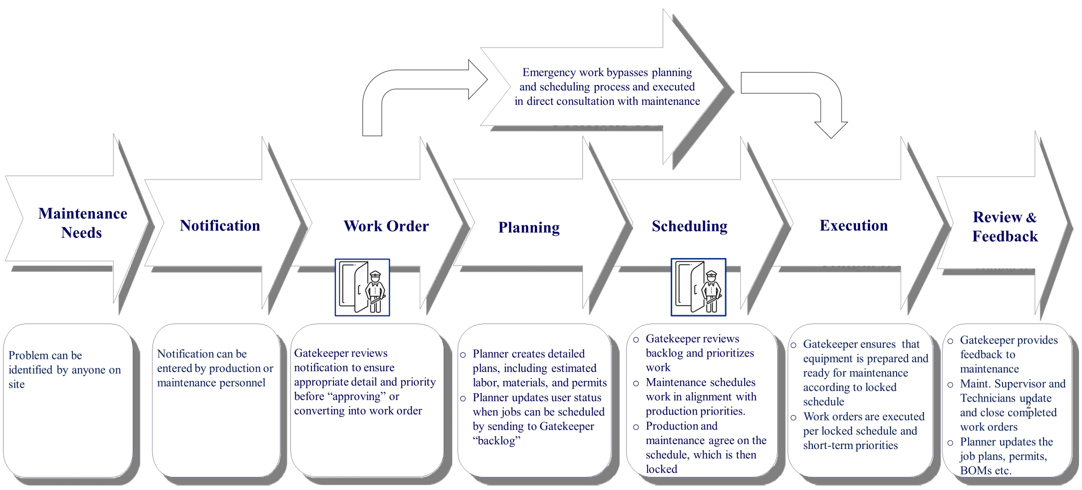

Figure 8. Improved maintenance work management process, illustrating the different stages

The role of the gatekeeper is considered the most critical in maintaining communication and coordination between the maintenance and production teams. Previously, the gatekeeper's role was not well-defined, leading to discrepancies and divergence in production and maintenance priorities. To improve wrench time, the following detailed expectations were set for the gatekeeper:

• Act as the liaison between production and maintenance teams, ensuring that equipment maintenance requirements are clearly communicated to the maintenance department.

• Serve as the primary manager of the area's maintenance backlog, overseeing the flow and prioritization of maintenance work.

• Review notifications to ensure accuracy, including correct equipment, issue descriptions, work centers, and appropriate priorities aligned with business needs. Upon thorough review, approve work notifications by converting them into work orders.

• Participate in the weekly schedule preparation meeting, provide priorities to the planner/scheduler to build the weekly schedule work from the "ready to schedule" backlog and commit to the locked schedule.

• Ensure that equipment is properly isolated and prepared for maintenance activities by arranging qualified production personnel for accompanying maintenance technicians to the job site, reviewing safety hazards, controlling, and issuing safety clearances for jobs involving special requirements or permits on the TASC (e.g., confined space, hot work, and working at elevated platforms, etc.).

• Provide feedback on the completed jobs for continuous improvement.

• Proactively inform maintenance of any emergency production needs.

It is crucial for production supervisors to meet production targets while ensuring that PM and PdM are completed to maintain overall asset health. Neglecting scheduled PM and PdM can lead to equipment failure and subsequent production losses. Therefore, the gatekeeper must communicate equipment availability for necessary maintenance service while striving to achieve their production targets. A work control application platform was introduced where:

• Weekly scheduled jobs (after the planner/scheduler publishes the schedule) can be put on hold until the gatekeeper or production supervisor confirms equipment availability.

• It provides the status of permit, clearance, and isolation requirements for each job.

• The maintenance supervisor can allocate resources once the equipment availability is confirmed by the production team.

Improved coordination between maintenance and production teams ensures that maintenance activities are seamlessly integrated into the overall operations of the plant, thereby reducing equipment downtime and enhancing asset reliability. The streamlined work coordination process is illustrated in Figure 9.

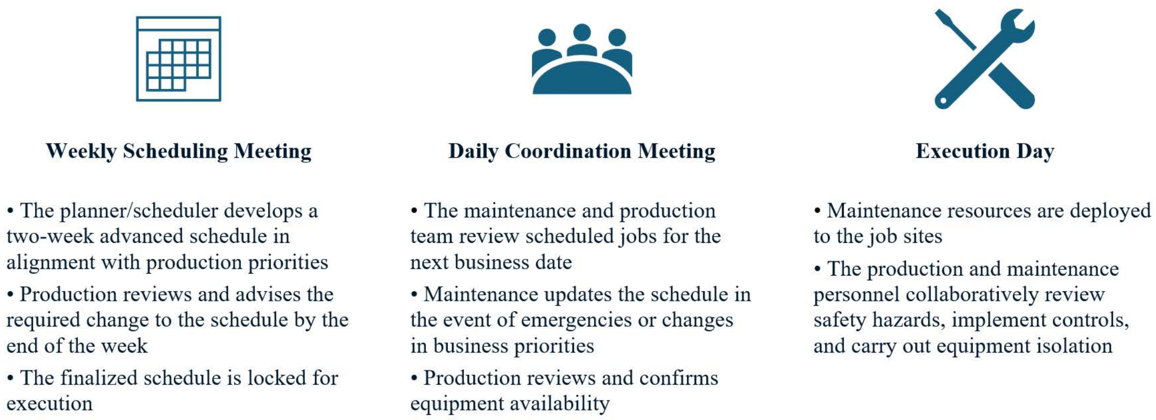

Figure 9. Streamlining work coordination process

In addition, a recurring issue observed is the lack of participation from the gatekeeper in the weekly schedule preparation meeting. This absence complicates the alignment of weekly work priorities and daily job coordination and can hinder the efficient handling of emergency situations. An attendance tracker was introduced to ensure the presence of representatives from each production area at the weekly schedule preparation meeting. This measure aims to enhance the alignment of maintenance schedules with production priorities, thereby improving the management of both routine tasks and emergency jobs. The introduction of an attendance tracker serves to foster accountability and ensure that all relevant stakeholders are engaged in the scheduling process. This approach is supported by findings that highlight the importance of integrated scheduling and improved communication in enhancing maintenance wrench time. A noticeable decrease in the work order backlog (outlined in Section 4.2) highlights that more work is being completed as a direct result of improved collaboration between maintenance and production, which in turn has led to enhanced operational efficiency.

4.1.2 Improving the management of parts and materials

The planners and technicians often struggle to find the right parts and materials because frequently used items are not consistently stocked, and BOMs are not regularly updated. This leads to longer waiting periods, contributing to a 4% loss in wrench time due to time spent searching for necessary parts and materials. To address this issue, a process was initiated to review completed jobs where materials or parts are used frequently and update BOMs accordingly. Additionally, a risk-based stock identification process was implemented to determine whether an item should be stocked. This process considered factors such as the consequences of not stocking the item, the probability of use (failure), and its lead time. Based on this evaluation, items were classified as either stocked or non-stocked, and inventory levels of stocked parts were adjusted accordingly.

Additionally, a new metric was introduced to track the usage of BOMs as a percentage of total planned work orders that utilize parts and materials. This metric aims to drive improvements in BOM creation. The planners actively collaborated with the inventory control group to create and update BOMs in the CMMS based on feedback from technicians. Additionally, planned jobs began with pre-kitted parts and materials, reducing the time spent traveling to the storeroom.

4.1.3 Implementing remote condition monitoring via IIoT

The implementation of remote condition monitoring technologies can significantly increase wrench time by addressing current issues related to reactive maintenance and unplanned equipment failure. When the study was conducted, maintenance personnel were often diverted from scheduled tasks to address unexpected breakdowns, which disrupted their workflow, caused reassignment, and reduced wrench time. Additionally, job breakdown requires troubleshooting and execution planning, further diminishing the wrench time. By integrating real-time equipment monitoring sensors and IIoT devices, the organizations can detect potential equipment failures before they occur [27]. The IIoT translates physical actions from machines into digital signals via sensors such as temperature, vibration, or conductivity sensors. The sensor data are processed, aggregated, and analyzed, and with the affordability of bandwidth and storage, massive amounts of data can be transmitted to provide not only a full picture of assets in a single plant but also an entire production network [28]. Using the data, the IIoT creates advanced prediction models and analytical tools to predict failures and respond proactively.

The chemical plant implemented pilot IIoT technologies in key process areas, including vibration, motor current, conductivity, and flow rate monitoring. This proactive approach allowed for timely planning and execution of maintenance activities, thereby reducing the need for emergency repairs and minimizing disruptions to scheduled work. Remote condition monitoring tools provide real-time data on equipment health dashboards, enabling early identification of anomalies and potential issues. As a result, maintenance personnel were able to focus on planned tasks rather than constantly reacting to unexpected breakdowns. The shift from reactive to proactive maintenance practices not only optimizes wrench time but also improves overall equipment reliability and reduces operational costs. The integration of advanced monitoring technologies is a critical step toward enhancing operational efficiency and maintaining a high level of equipment availability.

4.1.4 Improving schedule adherence

Improving schedule adherence is crucial for enhancing wrench time and overall maintenance efficiency. Schedule disruption causes non-value-added travel and reassignments for technicians. To address these disruptions, codes for schedule break-ins were established to categorize and track the causes of delays, such as technician unavailability, equipment unavailability, changes in production priorities, parts and material shortage, etc. By systematically recording and analyzing these disruptions, the underlying causes of schedule disruption were identified, and targeted corrective actions were developed.

For example, when frequent equipment unavailability was identified, corrective measures were implemented by improving coordination between the maintenance and production teams and refining planning for scheduled equipment downtime. Regular monitoring and reporting of these metrics ensure that corrective actions are effective, resulting in increased wrench time and more efficient resource utilization. Enhanced schedule adherence allows maintenance personnel to focus more on actual maintenance tasks rather than dealing with interruptions. It also boosts efficiency by reducing the need for last-minute adjustments and reassignment, leading to more effective use of resources and personnel.

4.1.5 Job aids and tool management

The maintenance technician typically completes tasks according to the written PM instructions. However, complex troubleshooting or rebuilding jobs often involve numerous sequential steps, which even experienced technicians may find challenging without immediate access to equipment manuals, drawings, job aids, or checklists. It was observed that technicians spent considerable time locating equipment information and determining the correct procedures during work execution. In many cases, engineering drawings were outdated, missing, or not readily available, causing significant delays in troubleshooting or rebuilding, which in turn reduced wrench time.

For example, mechanical crew 2 spent approximately 15% of his time on execution planning and scoping for troubleshooting jobs. Additionally, technicians often experienced further delays due to unclear directions, spending extra time searching for the necessary tools.

To address these challenges, prescriptive repair instructions and troubleshooting checklists were developed for the most common equipment and systems across the plant, with input from subject matter experts (SMEs). These tools were designed to help technicians perform complex rebuilding and troubleshooting tasks by providing sequential steps, thereby reducing execution planning time. Equipment-specific checklists for rebuilding and troubleshooting were created for pumps, conveyors, motors, fans, agitators, compressors, and other common rotating equipment. These checklists were issued with the work order to ensure technicians have the necessary guidance at hand.

Furthermore, an organized tool management system was implemented to ensure that technicians have immediate access to the necessary tools. This system includes clearly labeled tool storage areas, an inventory tracking system, and predefined toolkits for specific types of jobs, all of which help minimize the time spent searching for tools. Providing such structured information and tools facilitates more efficient maintenance processes, reduces downtime, and improves overall wrench time.

4.1.6 Limiting emergency work orders

Emergency work orders are a major contributing factor to schedule interruptions. Due to the high number of emergency work orders, maintenance personnel are frequently pulled from their regular PM and PdM tasks and reassigned to repair broken equipment. This causes work interruptions, distractions, and additional travel to reassigned job locations, leading to reduced wrench time. Furthermore, parts and materials are not pre-kitted for emergency jobs, forcing maintenance personnel to travel between the store and job site to find the necessary items. At the time of writing this report, emergency work accounted for approximately 20% of the total number of cases on site. Additionally, planners were sometimes bypassed for emergency work, resulting in duplicate work orders. When a work order is issued, the job may already be in progress under a duplicate order, leading to wasted time and resources.

Emergency or reactive work is more expensive than planned work. Therefore, a strong emphasis was placed on reducing the number of emergency work orders. When this study was conducted, there was no structured work prioritization process in place at the site, resulting in work being scheduled solely based on the ready-to-schedule backlog. This lack of prioritization often led to work orders with low business value, or 'false emergencies,' being selected and scheduled before high-impact work orders. This is evidenced by a high percentage of reassignments and emergency work. To address this issue, the ranking index for maintenance expenditure (RIME) methodology, developed by Ramond and Associates [29], was employed to prioritize and select work orders by considering equipment criticality, work priority, and the age of the backlog. The RIME methodology identifies which work orders have the highest business value and ranks them accordingly. A simplified RIME process, as shown in Tables 8–11 for work order prioritization, was implemented.

The planners were introduced to and trained in the use of the above methodology to prioritize work during their weekly schedule using RIME, ensuring that the highest-value work orders are selected and executed at the expense of lower-value work orders.

Table 8. A simplified RIME matrix for work order prioritization

Equipment Criticality (fixed)		**Maintenance Work Priority**				
		5 Emergency Safety/regulatory /breakdown	4 High Regulatory PM /potential breakdown	3 Moderate PM/PdM/SD work/adverse conditions	2 Minor Cost reduction /general maintenance	1 Low Standby equip. /nonproductive work
5	Safety/regulatory /environment	25	20	15	10	5
4	Production shutdown /no spare	20	16	12	8	4
3	Auxiliary support equipment	15	12	9	6	3
2	Non-production equipment	10	8	6	4	2
1	Building/structures	5	4	3	2	1

Table 9. Backlog age factor based on the work order passed target in weeks

Backlog Age Factor					
Weeks past target	1	2	3	4	5
Age factor	3	6	9	12	15

Note: Aged RIME Priority = Equipment Criticality × Work Priority + Backlog Age Factor

Table 10. RIME prioritization for work execution

Aged RIME Priority	Description
>25	Work must be completed immediately using all required resources.
16-25	Work must be completed as scheduled.
10-15	Work to be completed within 1-2 weeks.
5-10	Work to be completed within 2-3 weeks.
1-5	Work to be completed within 4 weeks.

Table 11. Work order prioritization example using RIME priority

Work Order	Equipment Criticality	Work Priority	Weeks Past Target	Backlog Age Factor	Aged RIME Priority	Execution Priority Description
10051396	4	3	2 weeks	6	18	Work must be completed as scheduled.
20038410	5	3	4 weeks	12	27	Work must be completed immediately.
20042009	2	4	1 week	3	11	Work to be completed within 1-2 weeks.
30133462	3	2	1 week	3	9	Work to be completed within 2-3 weeks.
...	...	...	...	...	...	...

4.2 Evaluating Wrench Time Improvement Initiatives

This study was conducted in the first half of 2023, and based on the findings, improvement initiatives were formulated in the second half of 2023. The implementation of these initiatives began at the start of 2024 and is currently underway. As shown in Figure 10, the OEE and backlog trends reflect the early impact of these initiatives on the maintenance process.

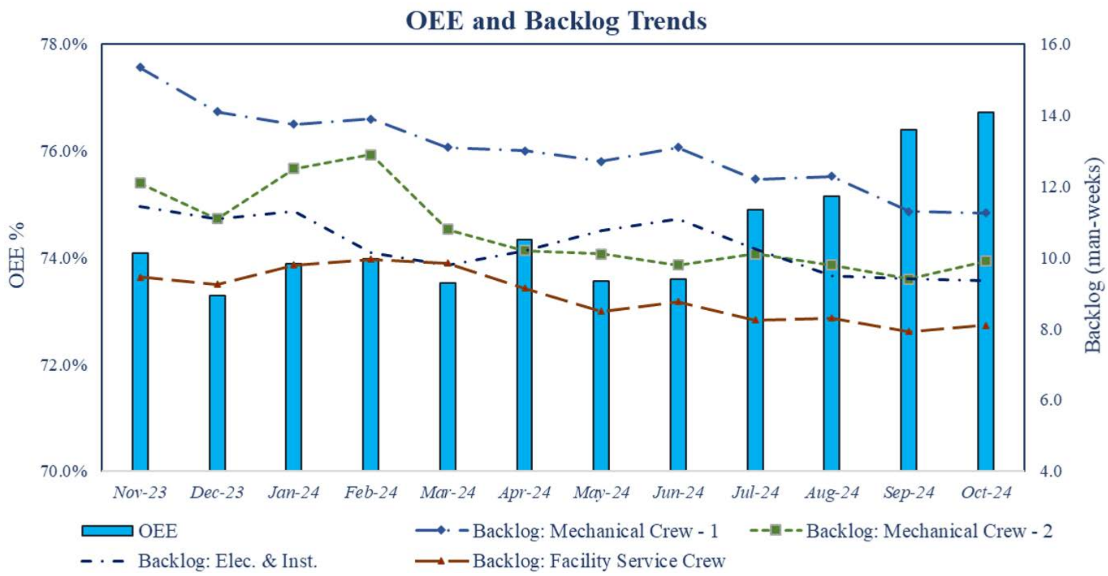

Figure 10. OEE and backlog trends reflecting the impact of wrench time improvement initiatives

The data indicates a clear reduction in backlog across all crews, with the backlog of mechanical crew 1 dropping from 15.3 man-weeks in November 2023 to 11.2 man-weeks by October 2024, alongside similar improvements for mechanical crew 2, electrical & instrument and the facility service crew. OEE also improved from 74.1% in November 2023 to 76.7% in October 2024, showing a positive shift in operational efficiency. These trends suggest that the wrench time improvement initiatives began to yield results, with a notable reduction in backlog and a steady increase in OEE. However, it is important to note that some initiatives are strategic and may take years to fully implement, with their full impact becoming more evident over time.

5 Conclusions

This study provides a comprehensive analysis of the wrench time within a chemical processing plant, highlighting both challenges and opportunities for improving maintenance efficiency. Through observation and data collection, a baseline wrench time of 28% was established, identifying significant losses due to inefficiencies such as inadequate coordination with production, scheduling disruptions, and unavailability of equipment, materials, and tools. These findings underscore the critical importance of effective work management processes, including robust planning and scheduling, improved communication and coordination between maintenance and production, and the utilization of advanced maintenance techniques. By addressing these challenges, maintenance personnel can focus more on value-added activities, ultimately increasing wrench time and contributing to the overall reliability and performance of the plant.

Several improvement initiatives were proposed and implemented, including enhanced coordination with production for equipment availability, better parts and materials management, robust work prioritization, deploying IIoT technology, and the development of detailed maintenance procedures and troubleshooting checklists. While no direct correlation exists between specific initiatives and the reduction in wrench time loss, each initiative is expected to positively impact multiple areas, leading to cumulative improvements in maintenance efficiency.

The current methodology involves statistical sampling, which requires considerable effort to collect data over time. Future research could assess the effectiveness of these initiatives, providing further insights and validating the strategies employed. In addition, future investigations could leverage technologies such as mobile apps, IIoT sensors, digital twins, augmented reality, and artificial intelligence (AI) to streamline work processes, gather real-time data on equipment status, and predict issues before they arise, reducing non-wrench time activities. By continuously monitoring and refining maintenance processes, it is expected to see increased efficiency, reduced downtime, and lower operational costs.

Ultimately, this research demonstrates that focusing on wrench time and systematically addressing inefficiencies can significantly enhance maintenance quality and plant reliability. As maintenance continues to evolve as a critical function within industrial operations, ongoing efforts to optimize wrench time will play a pivotal role in ensuring long-term sustainability and competitiveness.

Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The author declares no conflict of interest.

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