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THE IMPROVEMENT OF REWINDING WORKSHOP USING DISCRETE EVENT SIMULATION

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Abstract
The study investigates the efficiency optimization of the compressor rewinding workshop at King Abdulaziz University (KAU) using modelling and simulation analysis. The assessment starts with a base model showing current operations and identifies inefficiencies, including high completion and waiting times and overutilization of mechanics. Alternative scenarios, combining different numbers of mechanics and station resources, were analysed to identify the most effective configuration. The findings highlighted Scenario 9, including four mechanics and a single set of workstations, as the satisficing configuration. This scenario achieves a significant reduction in completion time (95.54 hours) and waiting time (43.77 hours) while balancing resource utilization (39.09 %).

The study underscores the value of simulation in streamlining complex workflows and demonstrates a cost-effective solution for improving operational efficiency. Practical implications include enhanced resource allocation and reduced maintenance delays, supporting KAU's efforts to maintain its extensive infrastructure.
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Key Words: Compressor Rewinding, Discrete Event Simulation, DES, Operational Efficiency, Resource Optimization, Scenario Analysis

1. INTRODUCTION

King Abdulaziz University (KAU), situated in Jeddah, Saudi Arabia, is one of the largest educational institutions in the region. With its wide campus buildings over 300 buildings, KAU serves a diverse population of students, faculty, and staff. Maintaining the operational efficiency of such a large infrastructure is a challenging duty, especially given the unique environmental challenges of Jeddah. Located on the Red Sea coast, Jeddah has a hot and humid climate for most of the year. These weather conditions put significant stress on the university's facilities, particularly its air conditioning (AC) systems [1]. As a result, the General Administration of Facilities Management plays a critical role in ensuring that KAU's buildings remain functional and comfortable.

Among the many challenges faced by the General Administration of Facilities Management, problems related to AC units are the most urgent. The combination of continuous usage and high temperatures leads to frequent breakdowns, making AC maintenance the highest cost and the source of most complaints. A particularly critical issue arises when the compressors in AC units are damaged. The compressors are not only the most expensive part of the maintenance process but also require significant time to replace due to procurement delays. Replacing a damaged compressor can cost from SR 25,000 to SR 300,000, making it the highest cost for the maintenance department.

Alternatively, the damaged compressors can be repaired, the repairing process called rewinding. Outsourcing compressor rewinding costs significantly less than purchasing new one, ranging from SR 15,000 to SR 70,000. To tackle this challenge and further reduce expenses, the General Administration of Facilities Management is working to make the rewinding workshop more active. By focusing on in-house rewinding and repairs, since the cost of in-house rewinding ranging from SR 500 to SR 3000, which covers only the cost of spare parts and does not include the wages of the workers involved in the process.

1.1 Rewinding workshop system and study objectives

The Rewinding Workshop at KAU, managed by the General Administration of Operations and Maintenance, is essential for maintaining compressors by performing wire rewinding for motor cores. This process includes disassembly, unwinding old wires, cleaning the core, rewinding with new wires, thermal treatment in an oven, and reassembly (see Fig. 1). Despite its importance, the workshop faces challenges due to limited resources: a single oven for thermal treatment, one disassembly and reassembly station, and two benches for winding tasks. These constraints lead to inefficiencies and delays in meeting the growing demand for repairs.

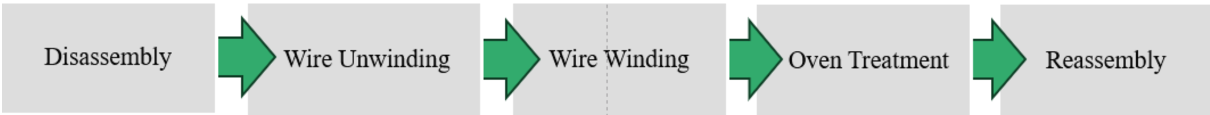

Figure 1: The rewinding process flow diagram.

By repairing compressors in-house, the workshop saves significant costs compared to outsourcing or purchasing new units. However, its current capacity and workflow are insufficient to manage the increasing workload, particularly for the labour-intensive rewinding process. This study makes a significant contribution by applying discrete-event simulation (DES) to analyse and optimize workshop operations, offering a data-driven approach [2] to identifying bottlenecks, improving resource allocation, and enhancing workflow efficiency. Beyond its practical applications, the study advances the academic understanding of simulation modelling in maintenance operations. It bridges the gap between theoretical constructs and real-world implementation, demonstrating how simulation can be effectively used for performance optimization.

The primary objectives of this study are to minimize the total completion time of the rewinding process, reduce waiting times, determine the optimal number of workers, and establish the ideal capacity for each station. These improvements will ensure better utilization of resources and enhanced maintenance performance [3].

2. LITERATURE REVIEW

Simulation modelling, particularly discrete event simulation (DES), has been widely used to optimize maintenance workflows, enhance resource utilization, and reduce costs across various industries. For example, a petroleum company used Arena simulation software to assess predictive maintenance strategies across pump shop operations, stores, and shipping departments [4]. Results demonstrated significant reductions in flow time (76 %) and waiting time (96 %), with no increase in work-in-process inventory, highlighting the potential of simulation to streamline maintenance workflows and support lean strategies.

In another case, a study on manpower planning for an electrical maintenance facility developed a simulation model to optimize resource allocation [5]. Arena software was used to model maintenance workflows and evaluate various scenarios, leading to improved resource utilization while meeting service levels. This study emphasized the practical application of simulation in balancing workforce demand and operational performance. DES has also been applied to improve production and assembly line efficiency [6]. In the mineral water industry [7], simulation identified bottlenecks and implemented preventive maintenance strategies, increasing production throughput by 54.03 % and reducing cycle times by 33.33 %.

Another study explored TV PCB assembly lines to identify workload imbalances and bottlenecks [8]. Simulation-driven resource reallocation significantly increased throughput and workload balance, demonstrating DES's role in optimizing resource utilization in assembly environments. Simulation has proven valuable in low-resource healthcare systems [9], where optimizing maintenance workflows for equipment and labour is critical. By combining DES and simulated annealing, a decision-support tool was developed to predict resource demands and prioritize maintenance requests. This approach enabled healthcare managers to optimize operational performance and improve service delivery cost-effectively.

In service contexts, DES has been used to model workflows in a printing shop [10], identifying solutions to reduce average queue waiting times to less than a minute by adding resources. Similarly, a study in the optics industry optimized workshop centralization, significantly reducing processing costs and delivery times [11]. Manufacturing studies have also showcased simulation's potential. An HVAC company used Simio software to evaluate cost-reduction opportunities, including minimizing work-in-process inventory and eliminating overtime labour, which improved throughput and reduced operational costs [12].

The insights from these studies are directly applicable to optimizing the rewinding workshop at KAU. By addressing bottlenecks, and reallocating resources, DES offers a robust framework for improving efficiency, reducing costs, and enhancing workflow performance in similar maintenance settings. This comprehensive literature demonstrates the versatility and effectiveness of simulation modelling, providing a solid basis for applying these methods to improve rewinding workshop operations.

3. METHODOLOGY

3.1 Study performance measures

To effectively assess and improve the rewinding process for compressor maintenance, key performance measures have been defined. These measures are designed to track the impact of the proposed changes and ensure that goals such as reducing overall maintenance time and maximizing the efficiency of resource usage are met. Table I provides a detailed breakdown of the selected performance measures.

Table I: Performance measures for rewinding process.

Performance measure	Description	Unit of measurement	Significance
Total average completion time	The cumulative time required to complete the entire maintenance process, from disassembly to final reassembly.	Hours	A key indicator of process efficiency; shorter completion times indicate improved workflow and reduced downtime.
Total average waiting time	The total time that the motor core spends waiting between different maintenance stages.	Hours	Identifies potential bottlenecks; lower waiting times indicate a smoother and more streamlined process.
Number of workers	The count of mechanics actively involved in the rewinding process at any given time.	Number (Mechanics)	Helps monitor labour utilization and balance workload; fewer mechanics with the same output suggests efficiency.
Number of stations	The number of different workstations utilized during the rewinding process (e.g., disassembly, winding, oven).	Number (Stations)	Indicates the effectiveness of resource use; optimal use of stations can lead to a more efficient process flow.

3.2 Study assumptions

To build both the baseline and alternative models effectively, the following assumptions were made to define the parameters and input variables for each scenario:

1. All compressors arriving for maintenance are assumed to have similar levels of wear and tear. Any extreme or unusual damage requiring specialized handling is not considered in the general workflow.
2. All necessary spare parts for motor core maintenance are assumed to be readily available in the workshop. There is no need to place special orders or wait for parts to be delivered.
3. The time taken to move parts between workstations is considered negligible, as is the distance between stations. Additionally, no extra workers are required for the transportation of parts.
4. All equipment and machinery in the workshop are in good working condition.
5. Workers are assumed to maintain a steady level of productivity throughout their shifts. There is no decrease in efficiency due to fatigue or other factors.
6. The simulation covers a period of 740 working days, which only includes active workdays. Weekends and holidays are excluded from this timeframe.
7. Compressors of varying sizes – large, medium, or small – are accounted for in the maintenance time based on a given statistical distribution, ensuring that size-related variations in processing time are integrated into the model.

3.3 Data sources and collection methods

The data for this analysis has been collected through a combination of methods. Interviews were conducted with the rewinding workshop manager and staff to get insights based on their practical experience with the rewinding process. Furthermore, data was taken from the IBM Maximo system, which provides automated records for compressor maintenance activities. Table II is a summary of the key data points collected, together with their descriptions, units of measurement, and methods of collection. This data has been utilized to analyse and enhance the efficiency of the rewinding process in our simulation models.

Table II: Input data for rewinding process workflow analysis.

Name	Description	Unit of measurement	Collection method
Arrival rate	Time when the compressor arrives at the rewinding workshop	Units per day	IBM Maximo system
Disassembly time	Time required to disassemble a compressor and remove the motor core	Hours	Staff input
Wire unwinding time	Time taken to unwind the old wires from the compressor's motor core	Hours	Staff input
Wire winding time	Time required to rewind the new wire onto the compressor motor core	Hours	Staff input
Oven treatment time	Time spent in the thermal oven for curing or heat treatment of the rewound motor core	Hours	Staff input
Reassembly time	Time taken to reassemble the compressor after rewinding and oven treatment	Hours	Staff input

3.4 Input data analysis

The collected data has been analysed using Arena Input Analyzer to identify the best-fit distribution for the arrival rate, which is used in the base simulation model for the rewinding workshop. For the other input parameters, staff input was used to generate approximate distributions since there was no historical data available for these variables Table III.

Table III: Input data for rewinding process workflow analysis.

Name	Probability distribution	Unit
Arrival rate	0.5 + Random.Weibull (0.915, 1.32)	Units per day
Disassembly time	Random.Triangular (7, 7.5, 8)	Hours
Wire unwinding time	Random.Uniform (1, 2)	Hours
Wire winding time	Random.Triangular (4, 5, 6)	Hours
Oven treatment time	8	Hours
Reassembly time	Random.Triangular (4, 6, 7)	Hours

4. MODELLING AND ANALYSIS

The goal of the modelling and analysis is to build a simulation of the KAU rewinding workshop. The first step started with analysing the current rewinding process, identifying areas for development, and assessing the possible effects of modifications. The model includes each step of the rewinding process, from the arrival of compressors to their final reassembly, covering disassembly, wire unwinding, rewinding, thermal oven treatment, and reassembly.

4.1 Simulation setup

The base and alternative models were run for 100 replications, with no need for a warm-up period since the goal was to examine the full 8-hour workday. The simulation was run for 740 days, reflecting the timeframe of the duration of the data collection used in this study. To ensure accurate results, the number of replications was selected to reduce the margin of error across all performance measures. Common random number streams were applied to the input distributions to minimize variance within the simulation outputs for both the base model and the alternative scenarios.

4.2 Base model

A base model of the compressor rewinding workshop at KAU was built using Simio simulation software [13]. Simio is a powerful discrete-event simulation tool that enables modelling of complex systems with dynamic interactions, allowing for detailed analysis of resource utilization, process flow, and system bottlenecks. Its object-oriented design and 3D visualization capabilities make it particularly useful for assessing real-world operational improvements. The model simulates the current workflow of the rewinding process. The process includes one disassembly station, a single bench for wire unwinding, one bench for wire winding, an oven for thermal treatment, and a reassembly station. The maintenance work is done by two mechanics and two electricians (see Fig. 2). The mechanics are responsible for disassembly, unwinding, and reassembly, while the electricians are in charge of the wire winding.

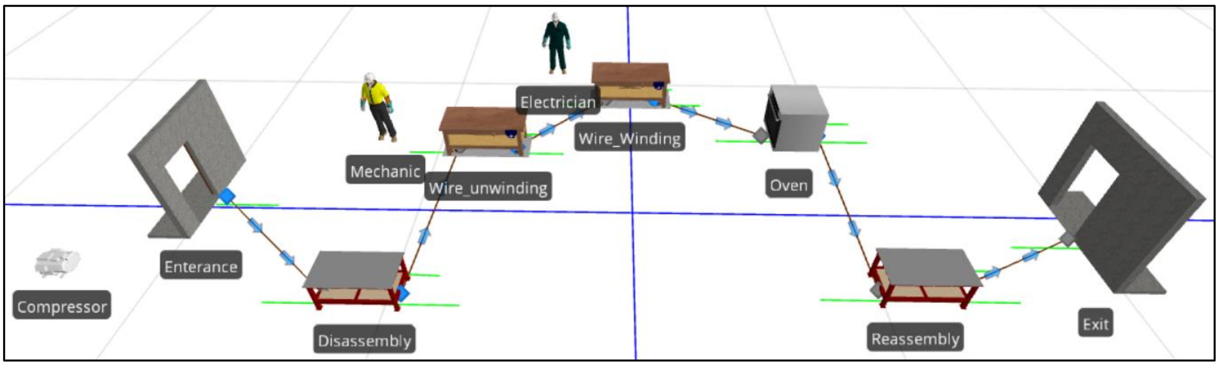

Figure 2: Rewinding workshop simulation model.

Upon arrival, compressors are initially disassembled by the mechanics to take out the motor core, followed by the unwinding step where the old wires are removed from the motor core (see Fig. 3). The electricians then perform the rewinding of new wires and then the motor core is sent to the thermal treatment in the oven. Finally, the mechanics reassemble the compressor. The model aims to accurately depict the existing conditions of the rewinding workshop to serve as a baseline for evaluating potential improvements [14, 15].

Figure 3: Motor core before the unwinding step (1), after unwinding step (2), and after the rewinding step (3).

4.3 Verification and validation of base model

The base model was verified throughout the model-building process by running multiple simulations and visually examining the outcomes to ensure accuracy. Moreover, a hypothesis test was carried out to validate the model's reliability. The simulated data presented an average of 414.1 generated entities over a 740-day period, with a minimum of 358, a maximum of 472, and a half-width of 4.4832. A comparison to the real data, which recorded 415 entities over the same time period, resulted in the following hypothesis test:

- **Null hypothesis (H_0):** The simulated entities accurately represent the true data.
- **Alternative hypothesis (H_1):** The simulated entities do not accurately represent the true data.

To perform a hypothesis test, a one-sample *t*-test [16] has been used to compare the mean of the simulated data (414.1) to the real-world mean (415). The goal was to determine whether the difference between the simulated and real data is statistically significant.

Information given:

- **Simulated data:** 414.1
- **Real data:** 415
- **Sample size (*n*):** 740 days
- **Sample standard deviation:** to be estimated from half-width
- **Half-width:** 4.4832

The half-width (margin of error) is given by the formula:

$$Half\text{-}width = t_{\alpha/2} \times \left(\frac{s}{\sqrt{n}}\right) \quad (1)$$

The sample standard deviation *s* has been estimated, and the *t*-test has been performed to see if the mean difference is statistically significant.

Hypothesis test results:

- **Estimated sample standard deviation (*s*):** 62.22
- ***t*-statistic:** - 0.39
- ***p*-value:** 0.694

Since the *p*-value of 0.694 was much higher than the typical significance level of 0.05, It means we fail to reject the null hypothesis (H_0). This suggests that the mean of the simulated data (414.1) was not significantly different from the real-world (415) during the 740-day period. The base model's generated entities can be considered accurate compared to real data.

5. THE RESULTS OF EXPERIMENTAL DESIGN

For the experimental design, four key control factors have been selected to test various scenarios within the simulation model because they have a significant impact on the overall performance of the rewinding workshop, unlike the wire unwinding and wire winding stations, which showed minimal effect on the workflow efficiency. These factors were:

- **Disassembly station capacity:** Two levels were considered: one disassembly station and two disassembly stations.
- **Oven capacity:** Two levels were considered: one oven and two ovens.
- **Reassembly station capacity:** Two levels were considered: one reassembly station and two reassembly stations.
- **Number of mechanics:** We varied the number of mechanics across four levels: 2, 4, 6, and 8 mechanics.

Each combination of these factors results in 8 different scenarios based on the number of mechanics, and when combined with the variations in the other factors, we have a total of 32 experimental scenarios, including the base model. This approach allows for a comprehensive assessment of how these factors influence the performance of the rewinding workshop.

5.1 Base model performance measures results

The performance measures for the base model have been evaluated to understand the current efficiency and workflow of the compressor rewinding workshop. These results provide a baseline for assessing the better scenario. The key performance metrics [17], including resource utilization, average processing times, and system throughput, are summarized in Table IV.

Table IV: Performance measures of base model for rewinding process.

Performance measure	Average	Maximum	Minimum	Half width
Total average completion time (hours)	623.0918	191.5417	1,646.7581	65.0622
Total average waiting time (hours)	560.091	127.7242	1651.099	66.9376
Number of workers	2	----	----	----
Number of stations	5	----	----	----

5.2 The other scenarios performance measures results

After running simulations for all experimental scenarios and comparing their outcomes with those of the base model, six scenarios were chosen for further analysis Table V. These scenarios were not necessarily the best-performing but were chosen to act as benchmarks for comparison against the base model. They clearly demonstrate the effect of varying the number of machines and workers, offering valuable insights for potential improvements in the rewinding workshop. Figs. 4, 5 and 6 show a comparison of the total average completion time, average total waiting time, and average mechanics utilization, respectively, across all scenarios.

Table V: Rewinding workshop scenarios comparison.

Model/Scenario	**Completion time** (hours)	**Waiting time** (hours)	**No. of mechanics**	**No. of stations**	**Mechanics utilization**	**Cost efficiency**
Base Model	623.09	560.09	2	5	96.26 % (High)	Overloaded
Scenario 8	1,048.97	989.3	2	8	96.47 % (High)	Inefficient
Scenario 9	95.54	43.77	4	5	39.09 % (Balanced)	Optimal
Scenario 12	95.24	43.69	4	7	39.31 % (Balanced)	Minimal Gains
Scenario 16	95.75	44.83	4	8	38.41 % (Balanced)	Higher Costs
Scenario 17	94.33	43.07	6	5	25.62 % (Low)	Underutilized
Scenario 24	90.53	41.6	6	8	24.07 % (Low)	High Cost

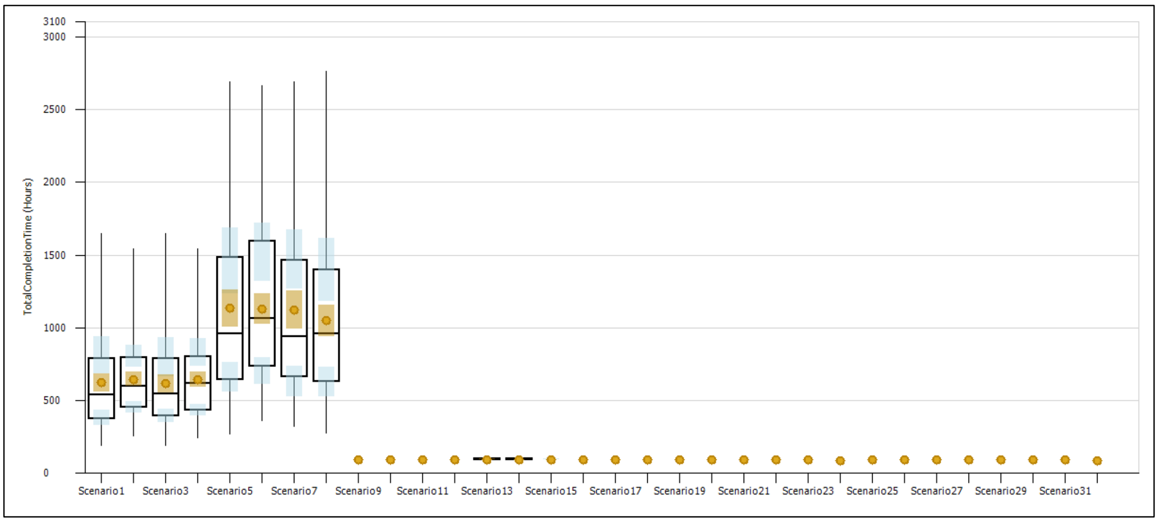

Figure 4: SMORE plot of "Total average completion time" for all scenarios.

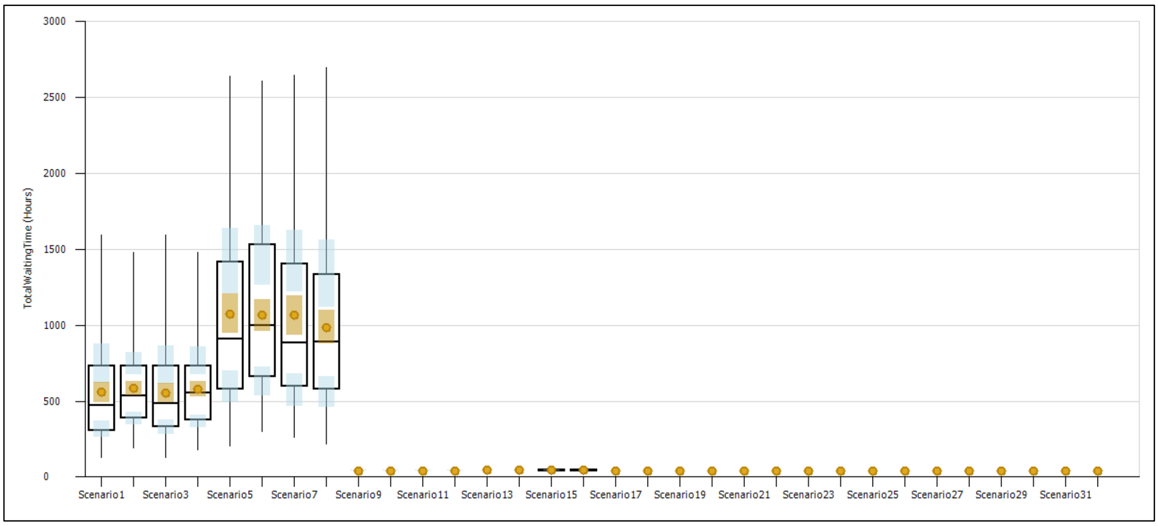

Figure 5: SMORE plot of "Average total waiting time" for all scenarios.

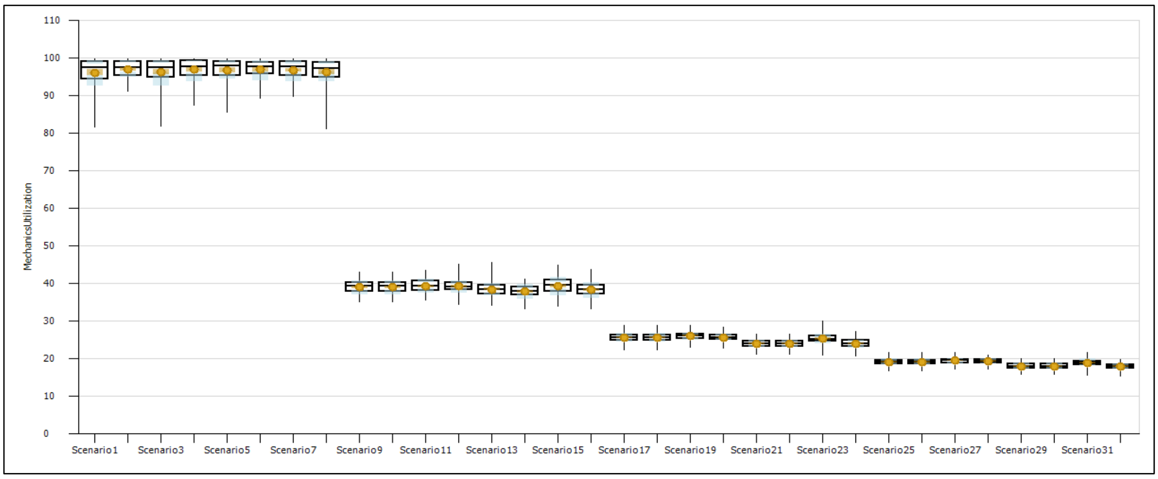

Figure 6: SMORE plot of "Average mechanics utilization" for all scenarios.

6. DISCUSSION OF RESULTS

This section presents a comprehensive comparison of the base model and the selected six scenarios. These scenarios were chosen to explore a variety of strategies for improving the efficiency of the compressor rewinding workshop. Key performance indicators, including Total average completion time, Average waiting time, Mechanics utilization, and the cost implications of increasing the number of workers and stations, were analysed to determine the most effective scenario for optimization.

6.1 Base model analysis

The base model, including 2 mechanics and 5 stations, was used as the initial benchmark. It presented a Total average completion time of 623.09 hours and Total average waiting time of 560.09 hours. Mechanics' utilization was very high at 96.26 %, indicating that the current setup was under a lot of strain, with mechanics consistently working at almost full capacity. This implies that in order to reduce bottlenecks, there is a need for extra capacity, either through more workforce or additional stations.

6.2 Scenario comparisons

1) Scenario 8 (Alternative One): This scenario, with 2 mechanics and an increased number of stations (2 disassembly, 2 ovens, and 2 reassembly), resulted in a Total average completion time of 1,048.97 hours and Total average waiting time of 989.30 hours. The mechanics' utilization increased to 96.47 %. Despite the addition of stations, the unchanged number of mechanics could not efficiently handle the workload, leading to poorer performance. This indicates that simply adding stations without an increase in mechanics may not resolve the bottlenecks.

2) Scenario 9 (Alternative Two): In Scenario 9, the number of mechanics was increased to 4 while maintaining one disassembly station, one oven, and one reassembly station. This resulted in a significant reduction in both Total average completion time to 95.54 hours and Total average waiting time to 43.77 hours. The mechanics' utilization dropped to 39.09 %, indicating a well-balanced workload. This scenario achieved the most substantial improvement in efficiency with a minimal increase in labour costs, making it a strong candidate for the optimal scenario.

3) Scenario 12 (Alternative Three): This scenario used 4 mechanics with one additional oven compared to Scenario 9. The Total average completion time decreased slightly to 95.24

hours, and the Total average waiting time was similar at 43.69 hours. The mechanics' utilization remained close at 39.31 %. The slight performance gains did not justify the added cost of the extra oven, suggesting diminishing returns with additional equipment.

4) Scenario 16 (Alternative Four): In this scenario, 4 mechanics were assigned to 8 stations (2 disassembly, 2 ovens, and 2 reassembly). The Total average completion time was 95.75 hours, and the Total average waiting time increased slightly to 44.83 hours. The mechanics' utilization decreased to 38.41 %, indicating that the workload was spread out, but not efficiently enough to justify the additional stations, leading to unnecessary costs.

5) Scenario 17 (Alternative Five): Scenario 17 increased the workforce to 6 mechanics while keeping the stations low (one disassembly, one oven, and one reassembly). It resulted in a Total average completion time of 94.33 hours and Total average waiting time of 43.07 hours, with mechanics' utilization at 25.62 %. Although performance improved, the low utilization suggests that the workforce was underutilized, and increasing labour without corresponding adjustments to stations did not yield proportional benefits.

6) Scenario 24 (Alternative Six): This scenario had the highest number of mechanics (6) and stations (8, including 2 disassembly, 2 ovens, and 2 reassembly). The results showed the best Total average completion time of 90.53 hours and the lowest Total average waiting time of 41.60 hours. However, mechanics' utilization was at 24.07 %, indicating a significant underutilization of resources. While performance was excellent, the cost of two additional mechanics did not justify the marginal improvement compared to Scenario 9.

6.3 Cost implications

A critical aspect of this analysis was understanding the trade-off between performance improvements and costs associated with additional resources:

- **Adding more mechanics:** Although scenarios like 24 showed the best performance in terms of completion and waiting times, the cost of employing two more mechanics outweighed the benefits. Scenario 9, which involved increasing the number of mechanics to 4, showed almost similar performance improvements without the need for additional stations, making it a cost-effective choice.
- **Adding stations:** Scenarios with more stations (like 8, 16, and 24) demonstrated that just increasing the number of stations does not guarantee better efficiency. Scenarios like 9 and 12, with balanced increases in workforce, produced substantial performance improvements without excessive station costs.

6.4 Selection of the best scenario

Based on a thorough analysis of performance metrics, resource utilization, and cost efficiency, Scenario 9 is determined to be the best scenario for improving the compressor rewinding workshop:

- **Performance gains:** Scenario 9 achieved a substantial reduction in completion and waiting times compared to the base model. It provided nearly the same efficiency gains as higher-cost scenarios but with lower resource expenditures.
- **Cost efficiency:** Scenario 9's configuration requires only two additional mechanics, leading to a reasonable increase in labour costs while avoiding unnecessary station expansions, as seen in Scenario 24.
- **Resource utilization:** The mechanics' utilization in Scenario 9 was 39.09 %, indicating a well-balanced and efficiently managed workload.

In conclusion, the comparative analysis highlights that Scenario 9 is the most suitable for implementation, offering substantial performance improvements while maintaining cost efficiency. This makes it the recommended choice for enhancing the compressor rewinding workshop's operations.

7. CONCLUSION AND RECOMMENDATIONS

This study aimed to enhance the efficiency of the compressor rewinding workshop at King Abdulaziz University by evaluating different resource configurations using discrete-event simulation. The analysis began with a base model representing the current workshop setup and expanded to test six alternative scenarios with varying numbers of mechanics and station resources. The results highlighted key inefficiencies in the current system, including excessive completion and waiting times and the overutilization of mechanics.

Among the tested scenarios, Scenario 9 emerged as the most effective solution, demonstrating an 84.67 % reduction in average completion time and a 92.18 % decrease in waiting times compared to the base model. This configuration, consisting of four mechanics with a single set of disassembly, oven, and reassembly stations, significantly improved workflow efficiency while maintaining balanced mechanic utilization at 39.09 %, preventing overloading.

Beyond operational improvements, this study reinforces the practical value of discrete-event simulation in optimizing maintenance workflows. By providing a data-driven framework for decision-making, simulation modelling enables facility managers to assess alternative configurations, predict system performance, and implement cost-effective solutions. The findings of this study offer a scalable approach that can be extended to similar industrial maintenance environments where resource constraints and process bottlenecks impact efficiency.

For future studies, further exploration should focus on refining assumptions, particularly by considering the impact of worker efficiency variations over time and the availability of spare parts to develop more precise simulation models. Additionally, a more comprehensive cost-benefit analysis is needed to further justify the selection of Scenario 9 and establish its long-term economic viability. Collecting more recorded data for stations processing times is also highly recommended. A more detailed dataset would allow for greater accuracy in analysing workshop performance and refining the proposed solutions. Furthermore, a full evaluation of the tools and equipment currently used in the rewinding workshop could identify areas for improvement, such as upgrading outdated machinery or adopting more efficient technologies. These studies would contribute to further enhancing the workshop's efficiency and overall effectiveness.

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