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Bottleneck Identification and Production Improvement in Manufacturing Systems Using Discrete-Event Simulation

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Abstract

In the highly competitive manufacturing industry, optimizing production processes is essential for improving efficiency, reducing bottlenecks, and minimizing production delays. This study employs JaamSim (Simulutaion tool) to perform Discrete-Event Simulation (DES) in order to analyze the production workflow at Geo Sondaj Makine AŞ., a drilling equipment manufacturer. The study thoughtfully explores seven key components, aiming to identify potential bottlenecks using queue metrics and machine activity data. Different strategies, such as increasing workstation capacities, implementing parallel multiple working stations, and dynamic resource allocation, were tested to improve throughput and reduce production time. Simulation experiments showed significant performance benefits, especially a 37.9% reduction in the production time of the HQ Core Barrel component, which demonstrates the effectiveness of the proposed improvements. Statistical analysis (confidence intervals: 90%, 95%, 99%) and graphical comparisons were performed to validate these improvements, which confirmed the reliable effectiveness of the implemented strategies. The results prove that DES is an effective tool not only for identifying bottlenecks but also for production optimization and decision-making in manufacturing. Future research should explore predictive models based on artificial intelligence to further improve performance and resource utilization.

Keywords

Discrete-Event Simulation, Bottleneck Analysis, Production Optimization, Manufacturing Efficiency, Parallel Workstations

1. Introduction

Robust and innovative strategies are needed to effectively manage the increasing complexity of modern manufacturing systems and improve production efficiency. A key challenge is the bottleneck phenomenon, where the production flow is interrupted at certain stages, causing delays and production losses. According to Ingemansson et al. (2005), automated simulation models are a reliable way to solve this problem, which helps in the timely identification and remediation of bottlenecks. These models provide the opportunity to digitize manufacturing systems and analyze performance in a virtual environment, without any practical intervention. This approach enables the identification of production defects, the effective allocation of resources, and the improvement of overall production efficiency, which makes the performance of the manufacturing system more stable and efficient.

To conduct a detailed examination of how various components interact over time, especially within the manufacturing and service environments, many organizations employ discrete-event simulation (DES). DES helps

identify hidden inefficiencies in complex systems that traditional analysis might overlook (Ingemansson et al., 2005). Through the simulation of production operations, manufacturers can precisely locate the stages at which bottlenecks occur. This information can then be used to make targeted improvements, such as adjusting machine configuration, optimizing workflow, or adding additional resources.

To analyze the effects of different target measurements on production output at the same time, Simulation-based COnstraint REmoval (SCORE) has emerged, a recent development in simulation technology that uses multi-objective optimization. This method helps to effectively identify and resolve bottlenecks in production, allowing for improvement in the overall system's performance. This capability facilitates in identifying existing bottlenecks and also allows for the evaluation of various improvement strategies. Through this, understanding the effectiveness of implemented strategies in alleviating the constraints and finding solutions that truly make a difference (Bernedixen 2018).

The strength of DES comes from its capacity to generate realistic variability and randomness, which replicates real-world disruptions, including unexpected delays or demand surges. This analysis helps teams identify particular areas where queues form at critical resources or uncover the tasks that take longer than expected to complete. In addition, DES offers risk-free experimentation through the testing of potential changes in virtual settings prior to actual implementation. This ability is important for both the identification of current constraints and the assessment of different mitigation strategies to address them (Venter 2017).DES has been used successfully by organizations in various industries, from manufacturing to healthcare to enhance their processes. They see the effects of changes on throughput and efficiency and analyze problems related to resource allocation or design of workflows. This leads to more informed decision-making and better operational performance (Septiyanto et al. 2022; Faget et al. 2005).

Improving production efficiency is vital in today's manufacturing due to its impact on cost, quality, and customer satisfaction. Persistent workflow bottlenecks continue to limit system performance. This study aims to analyze the production processes of Geo Sondaj Makine AŞ, a drilling equipment manufacturer situated in Ankara. The study focused on 535 Pump, Gearbox, Wireline, and HQ Core Barrel, to identify losses and provide recommendations through DES using JaamSim. Data from the facility ensures a realistic representation of production dynamics, including machine states, queue lengths, and workstation utilization in the model.

1.1 Objectives

The primary objectives of this study are:
-Identify bottlenecks within the production processes of seven key components (535 Pump, Gearbox, Wireline, Overshot, Rod Holder, Morset Box Equipment, and HQ Core Barrel).
-Utilize discrete-event simulation to analyze and improve manufacturing efficiency.
-Evaluate targeted optimization strategies for mitigating bottlenecks and improving throughput.

2. Literature Review

The optimization of mixed-model assembly line performance is a critical challenge in modern manufacturing, demanding a multifaceted approach that integrates analytical modeling with advanced simulation techniques. DES has emerged as a powerful tool for addressing this challenge, allowing for detailed analysis and optimization of complex systems. This literature review examines the role of DES, particularly when combined with analytical methods, in improving assembly line efficiency, focusing on work measurement, process design, and assembly line balancing.

Several studies highlight the effective use of DES for analyzing and optimizing mixed-model assembly lines. A notable approach involves integrating analytical modeling with DES to provide a systematic methodology for enhancing production system performance. Work measurement and process design, combined with industrial engineering techniques, form the foundation of this methodology. (Gunreddy et al. 2022) analyzed the identification of bottlenecks and optimization strategies using DES in a gear manufacturing production line. Using ARENA software, the production line was simulated, and various scenarios were tested. The results highlight the effectiveness of DES in streamlining manufacturing operations by reducing overall process time and increasing resource utilization. For emphasizing the value of virtual modelling using DES in identifying workstation-level inefficiencies, (Schindlerová et al. 2023) presented a case study on enhancing the assembly line production. The research highlights the significance of simulation in modern manufacturing by enabling rapid testing of multiple process variants.

A virtual twin of the production process was developed using the Witness simulation program to analyze and validate improvements. The study focused on identifying bottlenecks and redistributing work activities among

assembly station operators to enhance efficiency. The findings demonstrate the value of simulation in optimizing production workflows and supporting data-driven decision-making in industrial environments. (Edirisinghe and Karunarathne, 2023) used simulation modeling to identify bottlenecks in solid tire manufacturing, revealing the cushion layer-building process as the main constraint. Line Balancing and Pareto analysis confirmed this issue, while Cause-and-Effect and 5WHY analysis linked it to outdated machinery and power failures. Addressing these factors could enhance production efficiency by over 95%, demonstrating the value of simulation in process optimization. To improve real-time system responsiveness, (Singh et al. 2023) explored the impact of sensor manufacturing by integrating a DES based digital twin with IoT. This shows that simulation is increasingly used not only for planning but also for continuous improvement, aligning with the direction of our study.

(Patkar et al. 2024) explores the integration of analytical modeling and discrete event simulation (DES) to optimize mixed-model assembly line performance. The study presents a systematic methodology for work measurement, process design, and assembly line balancing using industrial engineering techniques. DES was implemented via AnyLogic® to evaluate key performance indicators such as mean flow time and capacity utilization. The findings highlight the effectiveness of DES in analyzing cycle time variations, optimizing workstation allocation, and improving overall line efficiency.

This research underscores the role of simulation in enhancing production system performance and decision-making in assembly line management. (Borbolla et al. 2024) explored the application of DES as a tool for optimizing production systems in industrial settings. Their research focused on an industrial progressive die stamping process, where DES was used to evaluate key performance indicators such as utilization rate and lead time, alongside environmental metrics like CO_2 emissions. Through simulation-driven scenario analysis, they demonstrated that DES could identify strategies to increase production capacity while minimizing environmental impact. This study underscores the role of DES in enhancing manufacturing efficiency and sustainability through data-driven optimization. Above mentioned studies layout the theoretical foundation of this study, where dynamic simulation approaches have been used to examine the production processes at a drilling equipment manufacturer situated in Ankara. The aim is to identify bottlenecks and evaluate targeted optimization strategies, such as increasing workstation capacities, introducing parallel operations, and expanding assembly lines.

3. Methodology

3.1 Simulation Tool

JaamSim is an open-source DES software. It is free to use and is commonly applied in fields such as engineering, logistics, manufacturing, and transportation to model and analyze processes. It is Java-based and features a graphical user interface (GUI), allowing users to create simulations without requiring programming knowledge. Key features include animation support, statistical analysis, and external data integration. An example of a simulation conducted using JaamSim is presented in Figure 1. Later, these simulations were explained through a flow diagram.

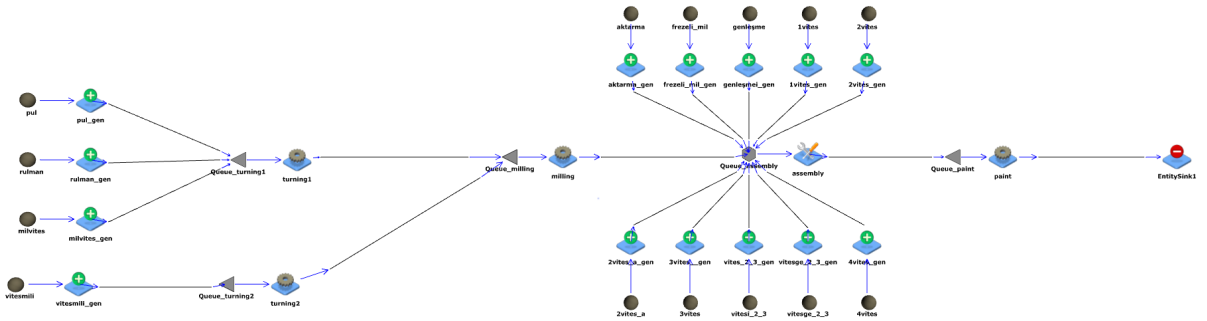

Figure 1. Simulation of Actual Production Line Created using JaamSim

3.2 Simulation Approach

To enhance system performance, discrete-event simulation was employed to analyze and optimize the production processes of seven key components: 535 Pump, Gearbox, Wireline, Overshot, Rod Holder, Morset Box Equipment, and HQ Core Barrel. The simulation model was developed using JaamSim, an open-source simulation tool, to replicate real-world manufacturing dynamics and identify inefficiencies.The data used in this study was collected from Geo Sondaj Makine AŞ, a manufacturing facility specializing in drilling equipment production. Data acquisition was conducted with the assistance of a mechanical engineer, who provided detailed information regarding production times, component specifications, and assembly line operations. This firsthand data collection

ensured an accurate representation of the factory's operational dynamics in the simulation model. The collected data was analyzed to validate model accuracy and compare optimization strategies. The log files provided crucial insights into system performance, allowing for adjustments in real-time decision-making.

The simulation experiments were executed over multiple replications, with detailed logs capturing the following:

- Queue lengths and waiting times at each station.
- Utilization rates of workstations.
- Machine state transitions, including breakdowns and tool changes.
- Total production time under different configurations.

The simulation model is based on the assumption that system parameters such as machine cycle times, breakdown rates, and resource availability remain consistent throughout each replication. The model follows discrete-event logic where events such as job arrivals, processing, and queueing are governed by stochastic distributions. Although this method offers flexibility and realism, it abstracts some human factors, external disruptions, or learning effects that might occur in real production settings. These limitations are inherent in simulation-based analysis and should be considered when generalizing results.

3.3 Bottleneck Identification Methods

Bottleneck detection was conducted through multiple methodologies to ensure comprehensive analysis. The methods applied include:

A. Queue-Based Bottleneck Detection

Queue analysis was used to determine stations experiencing excessive waiting times or congestion, indicating potential bottlenecks. Two primary techniques were utilized:
Queue Length Method: Measures queue lengths at each station over time. The station with the longest average queue length was identified as the most constrained resource, signaling a throughput bottleneck.
Waiting Time Method: Evaluates the time jobs spend waiting before processing. The station with the highest average waiting time was flagged as a constraint.

B. Active Period Method

This method, developed by Toyota Central Research and Development Laboratories (Roser et al. 2001), analyzes machine status logs to determine active periods. The machine with the longest uninterrupted active period was classified as the bottleneck, as it dictates overall system throughput. Working and idle time are the two distinct machine states that were closely monitored so that potential production bottlenecks and performance deficiencies can be identified and addressed in a timely manner.

3.4 Simulation Scenarios and Evaluation Strategies

After bottlenecks were detected, specific scenarios were designed to shorten production time and improve throughput. The strategies included:

- Increasing the number of workstations at identified bottlenecks.
- Capacity expansion for lathe, milling, and assembly stations.
- Combined improvements in multiple workstations when single-station adjustments were ineffective.

Each component's production process was analyzed under different configurations, and simulation results guided the selection of the most efficient optimization strategy. Following are the five different scenarios that have been used to improve production efficiency and eliminate bottlenecks in the production process of all the components under study.

- ***Scenario 1:*** A baseline scenario in which the current workstation capabilities and production setup were maintained without any changes, so that the results of other scenarios could be compared.
- ***Scenario 2:*** Lathe capacity was increased to eliminate bottlenecks in lathe operations, as the experiments showed high loads on lathe machines and bottlenecks in production flow.
- ***Scenario 3:*** The capacity of the milling workstation was increased to reduce queue lengths and waiting times and to eliminate delays in the milling process.
- ***Scenario 4:*** The capacity of the assembly station was increased, as the analysis revealed that delays during assembly affected production continuity.
- ***Scenario 5:*** The capabilities of lathes and assembly stations were increased simultaneously, to maximize production efficiency and ensure continuity in the manufacturing process.

These five scenarios are designed to identify bottlenecks, improve system performance, and increase productivity, to make the manufacturing system more efficient and resilient with the help of data-driven decisions.

Figure 2 below illustrates the flowchart of the simulation models of Scenario 1 and Scenario 2. Scenario 1 presents the current configuration of the main production line, where the workstation capabilities and production setup remain unchanged. This model helps to understand the basic flow of the production process and the material transfer system. In the same figure, Scenario 2 shows parallel workstations (turning and milling), which are introduced to reduce bottlenecks in lathe and milling operations and improve workflow. This model incorporates multiple parallel workstations to ensure a reduction in production cycle time and an increase in production efficiency.

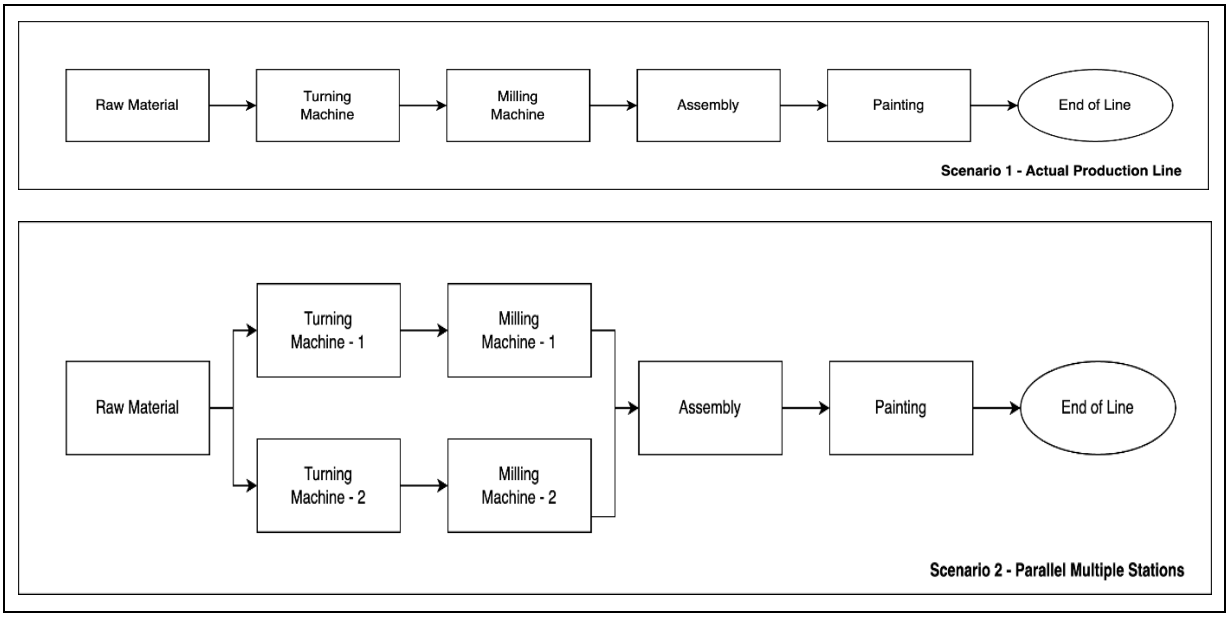

Figure 2. Simulation Models of the Main Production Line and Parallel Workstations (Scenario 1 & 2)

The simulation model of the production line with parallel multiple working assemblies as a flow diagram is presented in Figure 3.

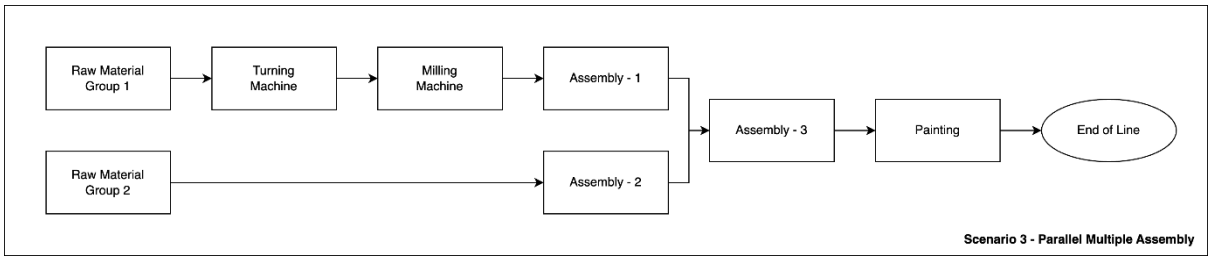

Figure 3. Parallel Multiple Assembly Diagram (Scenario 3)

The simulation model of the production line with parallel multiple working stations (turning and milling) and assembly as a flow diagram is as follows in Figure 4.

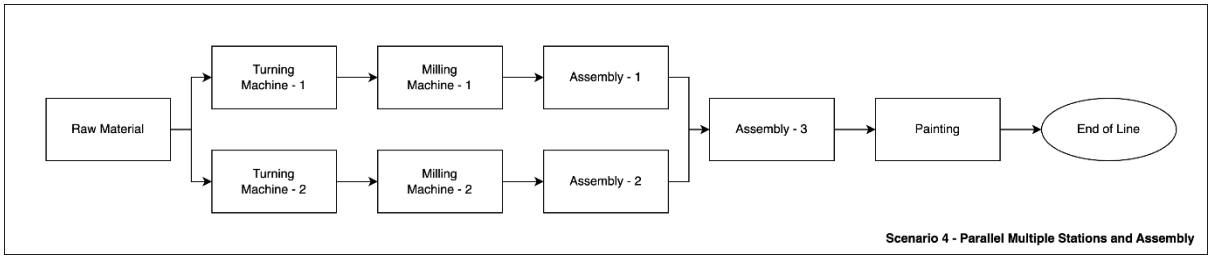

Figure 4. Parallel Multiple Stations and Assembly Diagram (Scenario 4)

3.5 Replication Number Analysis

To ensure the reliability of the simulation results, a replication number analysis was conducted using the following statistical approach. These calculations validate the reliability of simulation results by ensuring statistical robustness. The use of 90%, 95%, and 99% confidence intervals further strengthens the credibility of the performance evaluations:
The required number of replications (n) was determined using the utilization rates of the machines.

$$S = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \underline{x})^2}{n-1}}$$

S = Standard deviation

$\underline{x}$= Sample mean (average)

x_i= Each data point in the sample

n = Sample size

$$n = \left(\frac{Z_{\propto/2} * S}{E}\right)^2$$

n = Required sample size

$Z_{\propto/2}$= Z-score corresponding to the desired confidence level

S = Standard deviation (calculated using the formula above)

E = Desired margin of error

Where:

- is the Z-score for a 99% confidence level.
- represents the standard deviation of initial pilot runs.
- is the error margin (set at 0.02).

These calculations were performed by running the process five times, and utilization data was collected from all machines for each run. Using this data, the sample mean and standard deviation were calculated. By reducing random variations, this approach ensured statistically robust simulation outcomes.

4. Data Collection

To ensure the effective application of targeted improvements, a detailed analysis of the actual production time of all components under different scenarios was conducted. In this process, operational data was collected directly from each component of the production line at Geo Sondaj Makine AŞ, in order to accurately identify production speeds, potential bottlenecks, and improvement opportunities. This step was necessary so that the impact of improvement measures on production output could be objectively understood and corrective strategies could be effectively implemented.
Furthermore, to ensure accurate simulation of factory operations, data collected from direct observation were used, so that the operational dynamics of the factory could be truly represented in the simulation model. The simulation experiments were performed with multiple replications, in which detailed logs were recorded to allow a comprehensive analysis of the system performance. These logs included the following factors:

- Queue length and waiting time at each workstation
- Workstation utilization rate
- Machine state transitions, including breakdowns and tool changes
- Total production time under different configurations

Table 1. Production Times for the Actual Production Line

Component	Simulation Time (Hours)	Stations to be Increased
535 Pump	6.10	Lathe, Assembly
Gearbox	3.05	Milling, Assembly
Wireline	7.05	Milling, Assembly
Overshot	5.57	Milling, Lathe, Assembly
Rod Holder	6.75	Milling, Assembly
Morset Box Equipment	5.01	Milling, Lathe, Assembly
HQ Core Barrel	11.54	Milling, Lathe, Assembly

This detailed analysis not only helped in understanding the actual production time but also provided a solid basis for identifying potential bottlenecks in the production line and effectively implementing targeted improvements.

Table 1 below presents the initial simulation times for each component under the current production setup, along with the specific stations recommended for capacity increases to eliminate identified bottlenecks

5. Results and Discussion

The simulation results demonstrated significant improvements in production efficiency following targeted optimizations. The primary findings include:

Reduction in Production Time: Increasing milling and lathe stations led to substantial reductions in production time across all components, with the HQ Core Barrel component achieving a time reduction of 37.9%.

Bottleneck Mitigation: Queue-based and active period analyses effectively identified bottlenecks, and subsequent optimizations alleviated constraints at critical stations.

Effectiveness of Parallel Workstations: The introduction of parallel multiple working stations (turning and milling) significantly improved workflow continuity and reduced idle times.

Limited Impact of Assembly Expansion: Despite initial assumptions, increasing the number of assembly stations had minimal impact on reducing bottlenecks, except in the case of the 535 Pump component.

5.1 Validation of the Simulation Study

This simulation study was validated by comparing the simulated production times obtained from different operational scenarios with the expected performance improvements. Table 2 presents the initial and post-capacity increase production times, which demonstrate the accuracy of the simulation model.
For instance, the production time of the HQ Core Barrel component was reduced from 11.54 hours to 7.15 hours when the lathe capacity was increased, while for the 535 Pump component, it was reduced from 6.10 hours to 4.95 hours when both the lathe and assembly capacities were increased. These validated improvements offer clear decision-making insights for manufacturing managers to decide where to prioritize investments—whether in workstation expansion or parallel process design. Thus, the decisions can be guided by the quantified impacts observed through simulation, which results not only improve production metrics but also support strategic planning and resource allocation.

Table 2. Production Times for the Scenarios

Component	Initial Time (Hours)	Lathe Increased Time (Hours)	Milling Increased Time (Hours)	Assembly Increased Time (Hours)	Both Increased Time (Hours)
535 Pump	6.10	6.26	N/A	6.50	4.95
Gearbox	5.05	N/A	2.66	3.20	2.93
Wireline	7.05	N/A	5.59	7.30	5.82
Overshot	5.57	3.27	3.27	5.36	3.48
Rod Holder	6.75	N/A	4.39	7.18	4.91
Morset Box Equipment	5.01	3.03	3.03	5.47	3.57
HQ Core Barrel	11.54	7.15	7.15	11.84	7.26

This table compares the baseline and improved production times across five scenarios. It illustrates how different capacity increases at lathe, milling, and assembly stations impact system performance.

5.2 Numerical Results

Below, the example of simulation time calculation for a real scenario of 535 Pump components is explained. In this example, the simulation time is calculated with a 99% confidence level and a required error margin of 0.02, to ensure the accuracy and reliability of the results. The utilization rates obtained from the pilot simulation experiments were 0.5833, 0.571, 0.5682, 0.5917, and 0.5941. These rates were derived from various simulation experiments during the production process of 535 Pump components, which are important for analyzing the system performance and provide a basis for making decisions to improve the manufacturing process with high confidence. The observed improvements align with broader trends in manufacturing simulation literature, where DES is shown to significantly enhance decision-making under constraints.

$$mean = \frac{0.5833 + 0.571 + 0.5682 + 0.5917 + 0.5941}{5} = 0.5777$$

$$variance = \frac{(0.5833 - 0.5777)^2 + (0.571 - 0.5777)^2 + (0.5682 - 0.5777)^2 + (0.5917 - 0.5777)^2 + (0.5941 - 0.5777)^2}{4}$$
$$= 0.0001278$$

$$S = \sqrt{0.0001278} \approx 0.0113$$

$$n = \left(\frac{2.576 * 0.0113}{0.02}\right)^2 \approx 2.12$$

$$n = 3$$

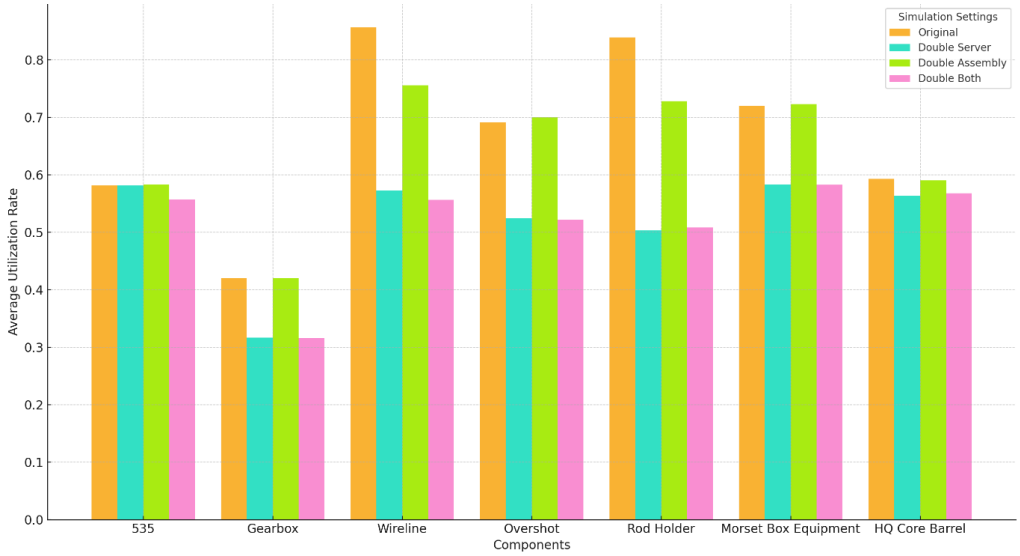

Figure 5. Average Utilization Rates for Components Under Different Simulation Scenarios

The bar graph in Figure 5 presents the average utilization rates of seven key components (535 Pump, Gearbox, Wireline, Overshot, Rod Holder, Morset Box Equipment, and HQ Core Barrel) under four different simulation settings (original, double server, double assembly, and double both). Each color represents a specific configuration, providing a clear comparison of component utilization. The graph shows that Wireline and Rod Holder remained in high utilization in most settings, while Gearbox showed particularly low utilization in both double server and double settings. This visual comparison helps in data-driven decisions to effectively allocate resources and improve production efficiency.

5.3 Graphical Results

Figure 6a provides an example of a queue analysis, showing the average waiting time, average queue length, and maximum queue length of component 535 in current setting. It can be seen that the assembly station had the highest waiting and queue lengths, marking it as the primary bottleneck. This analysis point out the targeted area for improving the performance of the assembly station, such as installing additional workstations, can help smooth the production flow and reduce queue lengths.

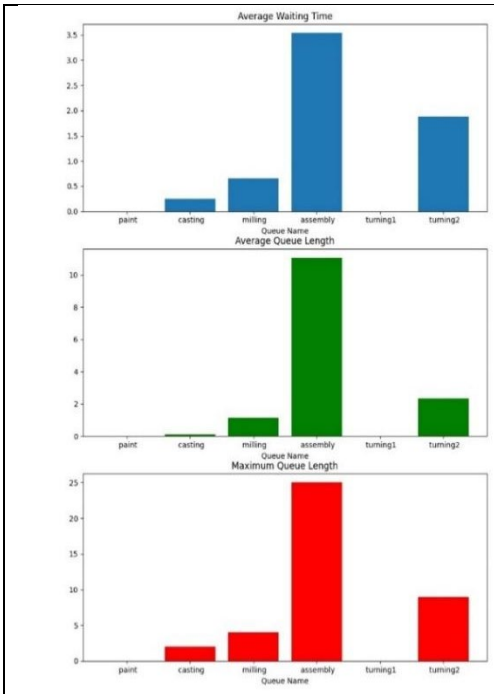

Figure 6a: current setting

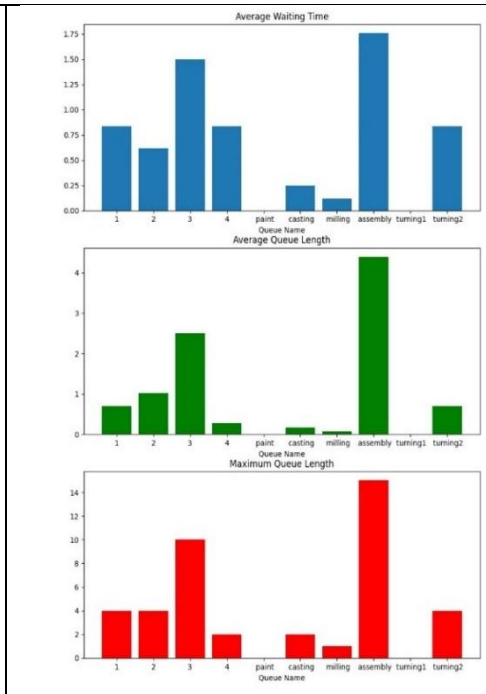

Figure 6b: After implementing different setting

Figure 6. Queue Analysis for the component 535

The graph presented in Figure 6b shows the performance of the production system after testing the scenario with the additional turning (Turning 1 and 2) and milling stations (Milling 3 and 4). It can be seen that the average waiting time, average queue length, and maximum queue length for component 535 with parallel multiple stations (turning and milling) and assembly help in analyzing the change in the production flow. The results show that the assembly station still remains as the main bottleneck with the highest waiting time and queue length. However, the addition of additional turning and milling stations has made the load distribution in the production line more balanced, which has made it possible to reduce waiting times and improve system performance. This assertion has also been examined by testing Scenario 4, whose comparisons with Scenario 1 can be seen in Figure 7. This comparative chart illustrates how increasing capacity in Scenario 4 significantly reduces average waiting times, queue lengths, and peak congestion across all components compared to the original system in Scenario 1.

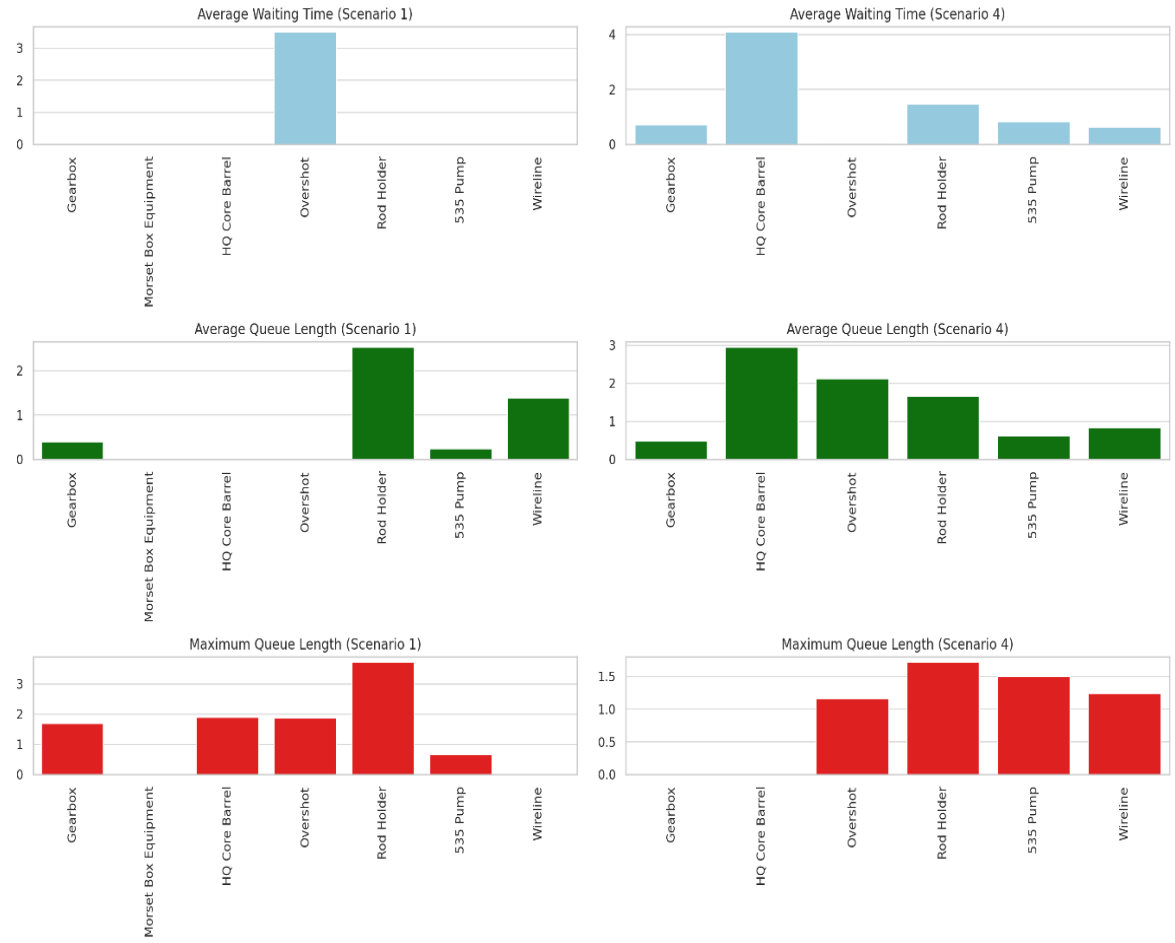

Figure 7. Scenario 1 vs Scenario 4 – All Components (Side by Side)

5.4 Proposed Improvements

A number of improvement proposals are put forth to mitigate the identified bottlenecks and improve the overall performance of the system. Increasing capacity at bottleneck stages—especially lathe and milling for components like HQ Core Barrel and Overshot—is strongly recommended. Parallel workstations will be implemented for turning and millin g processes to ensure continuous workflow and reduce process delays. Furthermore, dynamic resource allocation strategies based on real-time queue lengths and utilization rates need to be adopted to reduce waiting times and ensure efficient resource utilization. These improvements also include increasing assembly stations for components where assembly has been identified as a bottleneck, such as component 535 Pump. In addition, the production process can be further improved by continuously monitoring workstation utilization and incorporating automation tools to prevent bottlenecks. The implementation of these proposals is expected to significantly reduce waiting times, queue lengths, and overall production time, enabling significant improvements in the efficiency and productivity of the manufacturing system.

6. Conclusion

This study thoroughly examines the importance and utility of using DES for analyzing and enhancing production processes in a manufacturing environment. The primary objective of this study was to identify bottlenecks in production and implement targeted optimization strategies to effectively address them, resulting in significant improvements in throughput and overall performance.Based on the simulation outputs, it was observed that increasing workstation capacity, adding parallel stations, and using dynamic resource allocation effectively reduced bottlenecks. These measures not only helped to improve the production flow but also led to an increase in the fluidity and efficiency of the manufacturing process. The validation results also confirmed that the improvement in the manufacturing process are limited without data-driven strategies and advanced technological interventions. The research findings provide a clear direction for manufacturing industries to take advantage of advanced simulation techniques to increase productivity and improve operational efficiency.

While the results are promising, the model does not account for unexpected human errors, supply chain disruptions, or maintenance delays. In future studies, it would be valuable to explore hybrid simulation models and how they can be integrated with real-time data from IoT systems to support quicker and more accurate decisions on the shop floor.

Further research could also investigate the application of advanced AI methods—such as predictive bottleneck detection, using supervised learning techniques like decision trees or artificial neural networks. These models can be trained on historical machine logs and production data to forecast emerging bottlenecks in real time. In addition, reinforcement learning could be applied to develop dynamic scheduling policies that continuously adapt based on current system states, improving responsiveness and efficiency. Ultimately, this study demonstrates that simulation-based strategies are not only theoretical tools but also highly actionable solutions that can deliver measurable results and support informed, data-driven production decisions.

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References

Bernedixen, J. ,Automated bottleneck analysis of production systems: increasing the applicability of simulation-based multi-objective optimization for bottleneck analysis within industry (Doctoral dissertation, University of Skövde) , (2018). .

Borbolla, A., Aboujarra, M. N., & Ramanujan, D. , Investigating Sustainable Production Planning of an Industrial Progressive Die Stamping Process Using Discrete Event Simulation. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (Vol. 88391, p. V005T05A006). American Society of Mechanical Engineers, (2024, August). .

Edirisinghe, E. A. D. D. D., & Karunarathne, E. A. C. P. , Bottleneck identification through simulation modelling: a case of solid tire manufacturing sector. *Management Dynamics in the Knowledge Economy*, *11*(4), 324-337, (2023). .

Faget, P., Eriksson, U., & Herrmann, F. , Applying discrete event simulation and an automated bottleneck analysis as an aid to detect running production constraints. In *Proceedings of the Winter Simulation Conference, 2005*. (pp. 7-pp). IEEE, (2005, December). .

Gunreddy, N., Gupta, I., Poddar, I., Menon, A. P., Srivastava, R., & Saxena, A. K. , Bottleneck analysis for gear manufacturing unit by using discrete event simulation using ARENA. In *AIP Conference Proceedings* (Vol. 2653, No. 1). AIP Publishing, (2022, October).

Ingemansson, A., Ylipää, T., & Bolmsjö, G. S. , Reducing bottlenecks in a manufacturing system with automatic data collection and discrete-event simulation. *Journal of Manufacturing Technology Management*, 16(6), 615-628, (2005). .

Patkar, R., Ghanekar, M., Joladarashi, S., , Process Design and Performance Analysis of Mixed Model Assembly Line Using Analytical and Discrete Event Simulation Method," *SSRG International Journal of Industrial Engineering*, vol. 11, no. 2, pp. 1-15, (2024). . *Crossref,* https://doi.org/10.14445/23499362/IJIE-V11I2P101

Schindlerová, V., Sajdlerova, I., Bucko, M., & Klepková, L. (2023). Simulation and Optimisation of The Assembly Line Production Process. *MM Science Journal [s. l.]*, p. 6325–6332, 2023. DOI 10.17973/MMSJ.2023_03_2022104.

Septiyanto, A. F., Sarno, R., & Sungkono, K. R. , Identifying Bottlenecks of Hierarchical Process Model by Using Discrete Event Simulation and Process Mining. In *2022 IEEE 8th International Conference on Computing, Engineering and Design (ICCED)* (pp. 1-6). IEEE, (2022, July). .

Singh, P., Gupta, A., & Rao, S. , Real-Time Production Optimization through IoT-Enhanced Discrete Event Simulation. *Journal of Manufacturing Systems*, 68, 24–38, (2023). .

Venter, F. M. F. , Using a discrete-event simulation model to identify bottlenecks and determine the efficiency in a maintenance workshop, (2017). .