Improving Production Efficiency at Factoriffic Custom Lamps

Vu Quoc An

November 29, 2023

Abstract

Contents

Executive Summary

Objective: This study aimed to enhance the operational efficiency of Factory X, particularly focusing on identifying and addressing bottlenecks in two key machines.

Methodology: We employed comprehensive computer simulations, each encompassing 1000 trials, to evaluate the effects of varying production speeds and queue lengths. Rigorous testing and validation methods were integral to ensuring the model's reflection of real-world outcomes.

Key Findings:

1. *Queue Space Limitations:* The available space for lamps waiting for Machine 2 is insufficient. Our SME confirmed that increasing this space is not feasible due to operational constraints. Moreover, our simulations indicated that even with increased space, it would not effectively resolve the bottleneck issues, suggesting that the focus should be on other aspects of the system, particularly on enhancing production speed.

2. *Effectiveness of Speeding Up Machine 1 or Machine 2:* Speeding up Machine 2 leads to significant improvements in the system's efficiency. Doubling its production speed drastically reduced the average queue length from 32.7206 to 0.5319. In contrast, increasing the speed of Machine 1 had a minimal impact on reducing system queue lengths, indicating that Machine 1 is not a primary bottleneck in the current setup.

3. *Impact of a 25% Increase in Order Arrival Rate:* the order arrival rate increases by 25%, our simulation shows that the current system, with Machine 2's speed doubled, can effectively manage the increased demand. The average queue length at Machine 2 remains low at 1.0868 under these conditions, suggesting that the system is capable of handling a significant increase in orders without a substantial decrease in efficiency.

Testing and Validation: The simulation model underwent a comprehensive testing regime, including a 30,000-unit 'burn-in' period, followed by various tests such as unit, integration, and regression testing to ensure accuracy and reliability.

Recommendations:

- Prioritize enhancing Machine 2's production speed to directly address the main bottleneck and improve system efficiency.
- Prepare the factory for potential future increases in order volume by optimizing Machine 2, ensuring sustainable productivity.

1 Introduction

In this report, we examine the production processes at Factoriffic Custom Lamps, specifically focusing on Factory X. Our goal is to improve how the factory operates, especially in anticipation of more orders following a recent advertising campaign.

Primary Objectives: We are concentrating on two main areas: first, checking whether the waiting space for Machine 2 is big enough; and second, exploring whether making Machine 1 or Machine 2 faster would improve the overall system.

Methodology: We used a simulation program developed in Julia to test different scenarios in the factory. Initially created by another engineer, we thoroughly reviewed and validated this program, adjusting and fine-tuning as necessary to ensure accurate and useful results.

Early Findings: Our preliminary observations suggest that the waiting area for Machine 2 may be inadequate. While increasing the speed of either machine does seem to help, the extent of this benefit varies depending on factors such as a potential 25% increase in orders.

2 Background

2.0.1 The system

Our study focuses on the manufacturing process at Factory X, particularly involving Machine 1 and Machine 2.

Operational Process: The process begins with lamp orders entering a queue for Machine 1. After being processed, they move to a second queue for Machine 2. One notable challenge is the limited queue space before Machine 2, which can hold only four orders at a time. If this limit is reached, Machine 1 must pause until more space is available.

Completion and Delivery: Once processed by Machine 2, the lamps are ready for shipping to customers, marking their journey's end through the production line.

2.1 Schematic Diagram

The schematic diagram (Figure 1) visually lays out the factory's layout and key components. It shows the order flow from the initial queue for Machine 1, through processing, to the subsequent queue for Machine 2, and finally to shipment readiness.

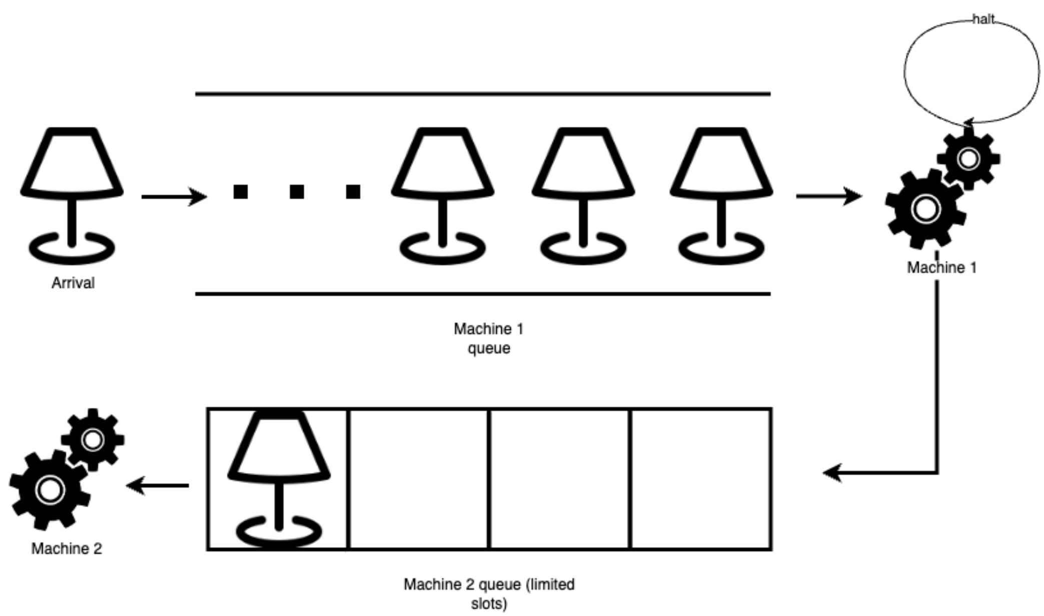

Figure 1: Schematic diagram of the Factory X production line.

2.2 Event Diagram

The event diagram (Figure 2) illustrates the sequence of events in Factory X's production line, starting with an order's arrival and tracking the process through Machine 1, queuing for Machine 2, processing at Machine 2, and culminating in the shipping of the final product. This diagram is crucial for understanding the dynamic interactions and dependencies within the production line.

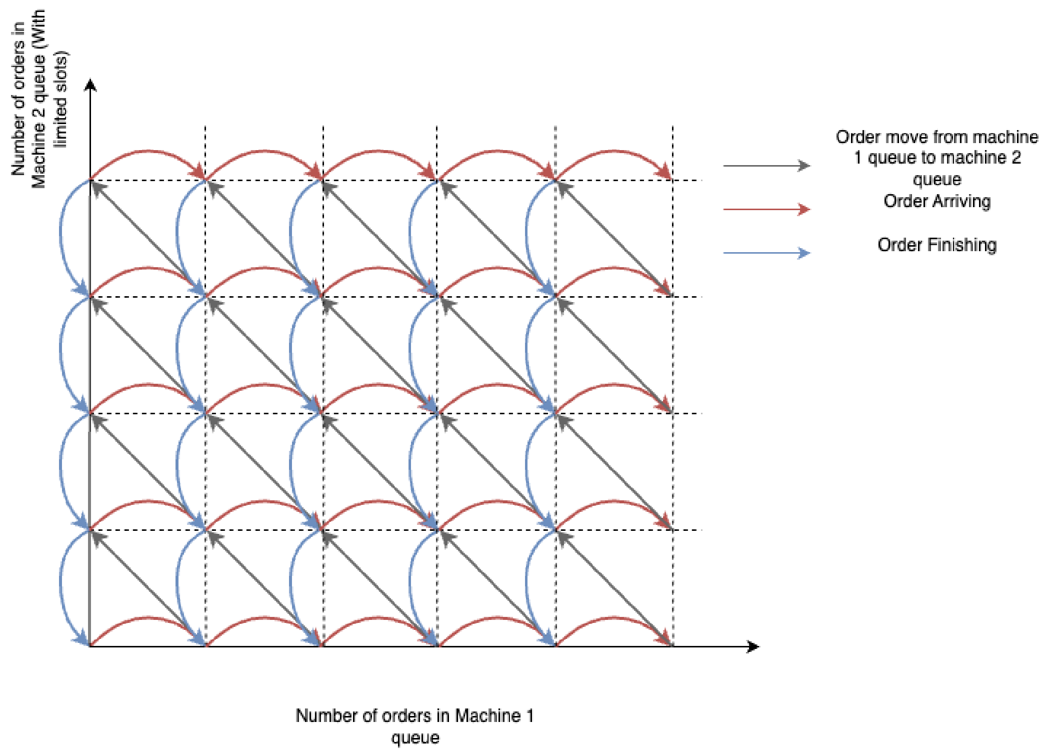

Figure 2: Event diagram of the Factory X production line.

2.3 Flow Chart

The flow chart (Figure 3) provides a detailed look at the decision-making process within the production line. It includes steps from order arrival, through processing at both machines, to readiness for shipping, highlighting the factory's operational logic.

2.4 Event Graph

The Event Graph (Figure 4) provides a visual representation of the varies events of the system. One noteworthy point is that once the service end, but the queue length 2 is at limit the service 1 will be pending until queue length 2 is free.

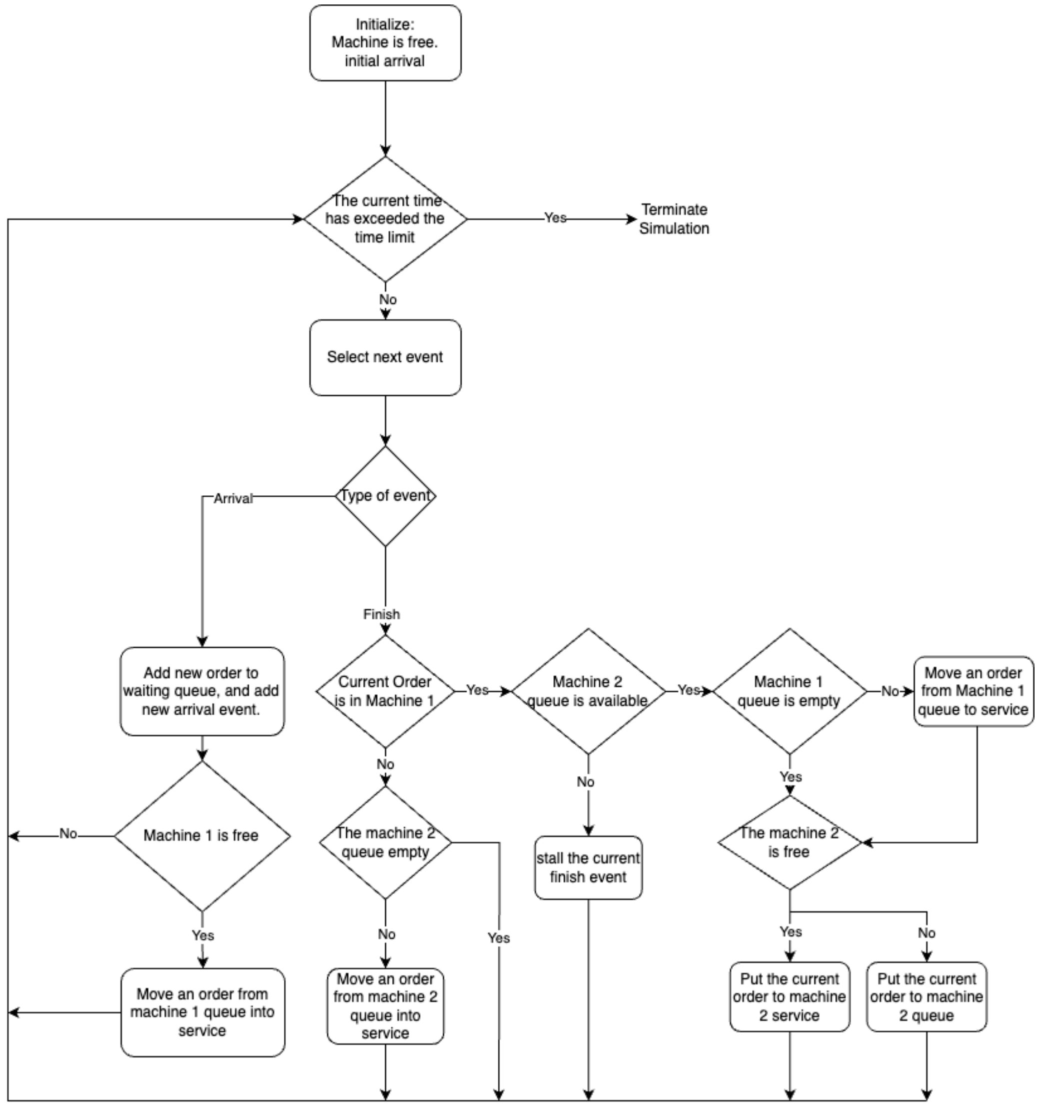

Figure 3: Flow chart of the Factory X production line.

2.5 The Simulation

2.5.1 Model Assumptions

This section outlines the foundational assumptions of our simulation model, which are essential for ensuring its validity and guiding the interpretation of

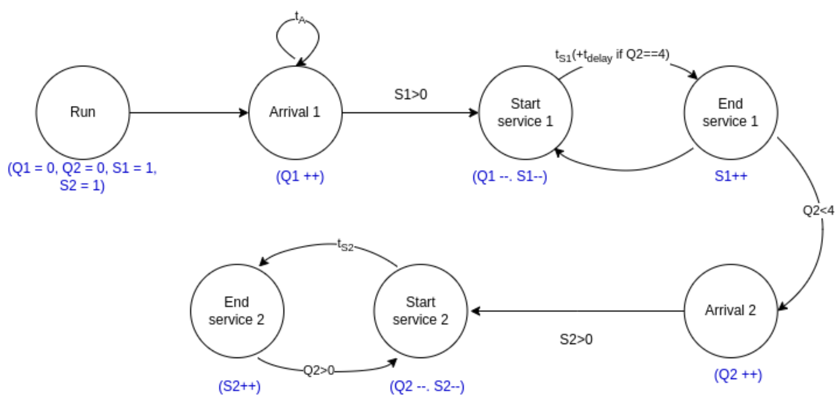

Figure 4: The Event Graph of the Factory X production line.

results.

1. **Distribution of Service Times:** We assume that the processing times for both machines adhere to specific statistical distributions. Machine 1's processing times are modeled with a *Normal distribution*, reflecting consistent operation patterns. Machine 2's processing times follow an *Exponential distribution*, capturing the variability in its operations.

2. **Inter-Arrival Time Distribution:** The arrival of orders is modeled using an *Exponential distribution* to reflect the random and independent nature of customer order placement.

3. **Queue Input Ordering and Independence:** The queuing system for both machines is assumed to operate on a *First-In, First-Out (FIFO)* basis, consistent with standard manufacturing procedures. We also assume that the arrival of orders and the processing times of the machines are independent events.

4. **Absence of Priorities and Pre-emption:** The model does not incorporate any prioritization or pre-emption in processing. All orders are treated equally and completed without interruption.

5. **Queue Capacity Limitations:** The model includes a constraint in the waiting space for Machine 2, limiting it to a maximum of four

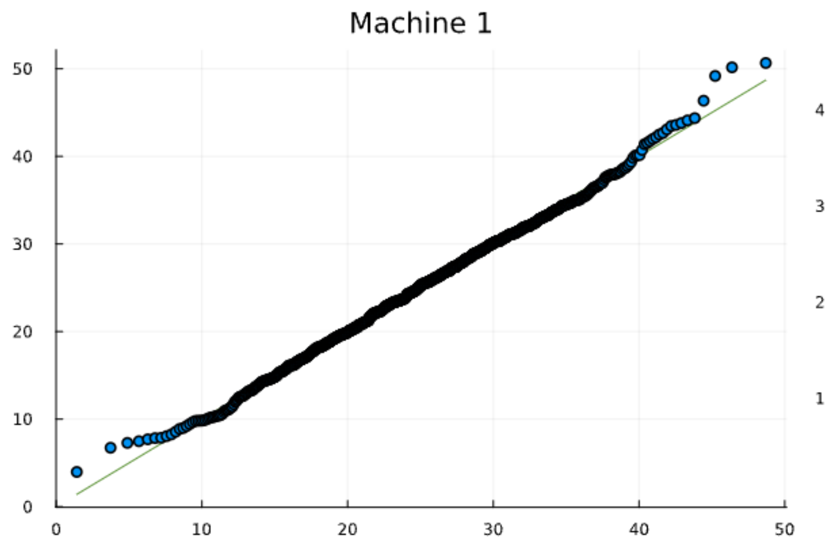

Figure 5: QQ plot of Machine 1's processing times against a normal distribution $N(25, 7.18^2)$.

queued orders. This limitation is crucial for analyzing system throughput and efficiency.

6. **Specific Distribution Times:** The production time for Machine 1 is assumed to follow a normal distribution with a mean of 25 and a variance of 7.18^2, while Machine 2's production time and the order interarrival times are modeled with exponential distributions with means of 59 and 60, respectively.

The validity of these assumptions was corroborated through QQ plots (Figures 5, 6, and 7), which graphically confirm our distributional assumptions for both processing and inter-arrival times. The close alignment of the collected data with these distributions supports the reliability of our model.

2.6 Verification

To ensure the simulation codebase's accuracy and reliability for Factory X, extensive testing was carried out. This section details the methodologies and outcomes of these tests.

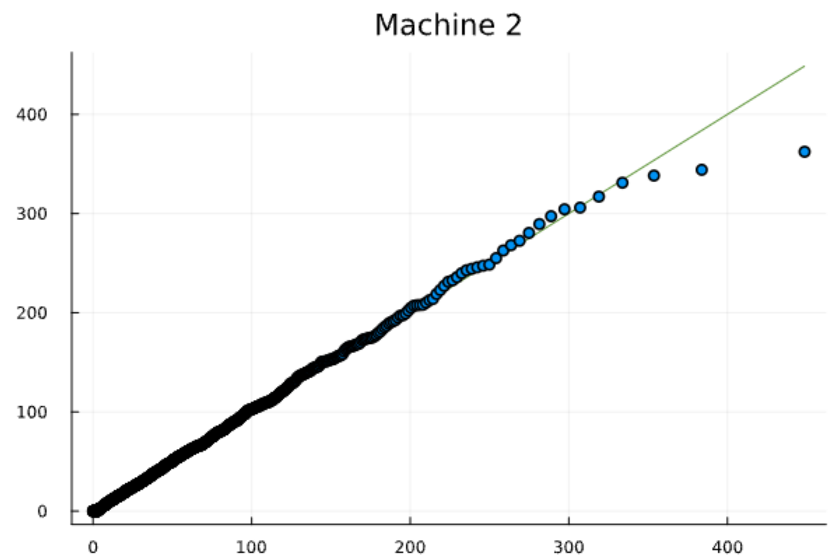

Figure 6: QQ plot of Machine 2's processing times against an exponential distribution exp(59).

2.6.1 Unit Testing

The objective of the unit testing was to validate individual components of the codebase. This testing focused primarily on initializing functions and randomization processes. Each unit test was designed to check the functionality of component functions. A key finding was that the initial codebase used deterministic time for Machine 1 instead of Normal distribution time. We have done a sensitivity test following the determine if this would effect the simulation result.

2.6.2 Integration Testing

Integration testing aimed to verify the combined functionality of multiple code components. This included conducting tests covering critical logic paths within the main simulation. Scenarios such as new order completion in Queue 1 when Queue 2 is full, new order completion when Queue 2 is available, order completion in Queue 2, and the arrival of new orders when Machine 1 is occupied were tested. The integrated components functioned as expected in all these scenarios.

We also test running the whole simulation on 1000 seeds with multiple

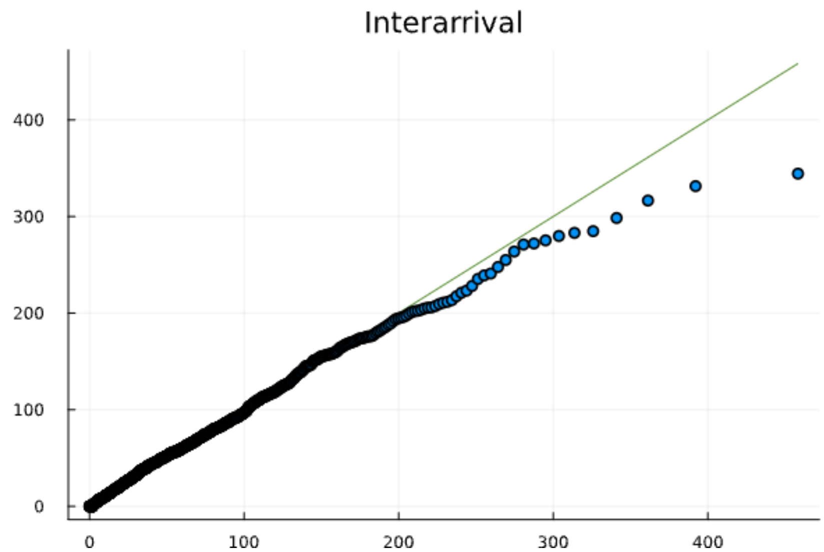

Figure 7: QQ plot of interarrival times against an exponential distribution exp(60).

parameters, the result all come out as with reasonable expected values.

2.6.3 Regression Testing

The purpose of regression testing was to ensure that new code changes did not negatively impact existing functionalities. This involved the continuous execution of test code after every modification. No regression issues were identified, ensuring that all modifications maintained the integrity of the code.

2.6.4 Performance Testing

Performance testing focused on evaluating the efficiency of the simulation code, particularly how the execution time varied with different simulation parameters. Results confirmed that the code's performance scales efficiently with increased simulation complexity, exhibiting O(n) time complexity, as depicted in Figure 8.

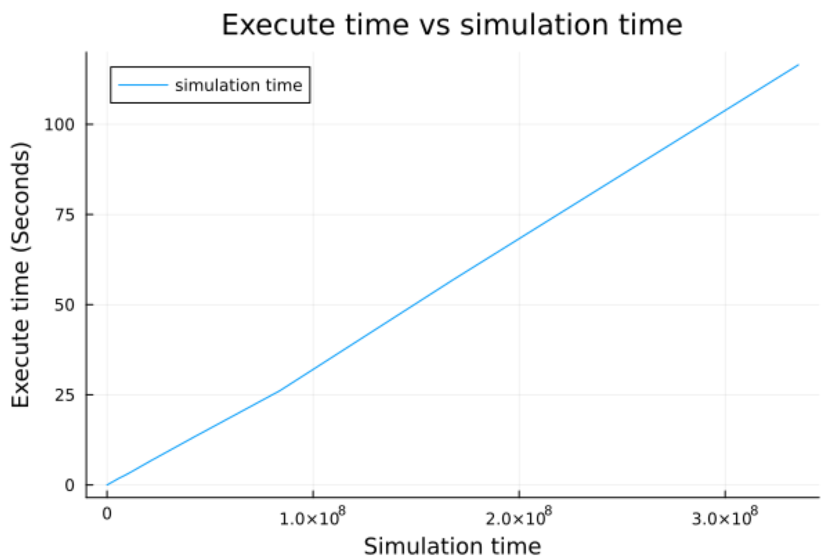

Figure 8: Simulation execution time

2.7 Validation

Validating our simulation model was a crucial step that combined empirical testing and expert insights to ensure accuracy and reliability.

2.7.1 Consultation with Subject Matter Experts

The validation process was significantly informed by discussions with Subject Matter Experts (SMEs), who provided essential confirmations and insights:

- **Queue Management:** SMEs verified that Factory X operates on a First-In, First-Out (FIFO) basis for order processing, with no prioritization or preemption in handling orders. This confirmation is vital for accurately modeling the flow of orders.

- **Operational Consistency:** The continuous and uninterrupted operation of the machines, with no breakdowns, was confirmed by the SMEs, aligning with our simulation assumptions.

- **Queue Space Feasibility:** Importantly, the SMEs indicated that increasing the queue space for Machine 2 is not a feasible option due to high costs and operational constraints. This insight was pivotal in shaping our recommendations.

The insights from SMEs enhance the credibility of our simulation, ensuring it reflects the actual operational conditions at Factory X.

2.7.2 Empirical Testing of Data Assumptions

We complemented the SME consultations with rigorous empirical testing of the system's key elements, including the interarrival times of orders and the production times for both machines. The testing results, presented in Figures 5, 6, and 7, corroborated our theoretical models, lending empirical support to our assumptions.

The combination of expert insights and empirical evidence solidifies the trustworthiness of our simulation model. This robust validation approach ensures that our model is a reliable representation of Factory X's operations, forming a strong foundation for our proposed operational improvements and strategic decisions.

2.7.3 Sensitivity Analysis

We performed a test to see if setting the machine production time differently affects our system. The test was conducted in two scenarios, each with 1000 trials:

- One with a fixed (deterministic) production time.
- Another where the production time varied, following a normal distribution with a standard deviation of 7.18 minutes.

We measured the queue length at the second machine in both scenarios. Our objective was to find out if the method of setting production time significantly impacts the queue length. The results are presented in the table below:

T-Test Results:

Test Statistic: -0.7551
P-value: 0.4503
Degrees of Freedom: 1994.0

The high P-value from the T-Test suggests that the differences in production time settings (deterministic vs. normal distribution) do not significantly

Measurement	Deterministic	Normal distribution
Mean	3.5364	3.5282
Standard Deviation	0.2454	0.2424
Margin of Error	0.0152	0.0150
95% Confidence Interval	(3.5212, 3.5516)	(3.5131, 3.5432)

Table 1: Comparison of Deterministic and Normal Distribution Settings for Machine 1, measuring average queue length at Machine 2, with a burn-in period of 30000, in a 100000 time simulation

impact the queue length at Machine 2. This aligns with our understanding that Machine 2 is the main bottleneck in the system, and thus variations in Machine 1's production time do not substantially affect Machine 2's queue.

3 Results

3.1 Mathematical Analysis of the Production System

This section presents an efficiency analysis of a production system comprising two machines with different production times and queue characteristics. The analysis involves three scenarios: the original system, improvement with doubled Machine 2 speed, and further enhancement by reducing the interarrival time by 20%.

System Parameters and Formula:

- Interarrival time of orders: follows an Exponential distribution.
- Machine 1's production time: Deterministic, constant.
- Machine 2's production time: follows an Exponential distribution.
- Machine 1 has an indefinitely large queue space.

The system is modeled as an M/M/1 queue, where the average queue length (L) is calculated using:

$$L = \frac{\rho}{1 - \rho} \tag{1}$$

where ρ is the traffic intensity (λ/μ).

Scenario Analysis:

1. *Original System:* Interarrival time = 60, Machine 2 production time = 59. Resulting L $\approx$ 59.
2. *Doubled Machine 2 Speed:* Machine 2 production time halved to 29.5. Resulting L $\approx$ 0.967.
3. *Reduced Interarrival Time by 20%:* Interarrival time decreased to 48 (20% less than the original). Resulting L $\approx$ 1.595.

The original system, with a queue length limited to 4, proves inadequate when compared to the much higher calculated average queue length of approximately 59, suggesting a significant risk of bottlenecks. While theoretical adjustments, such as doubling the speed of Machine 2 and reducing the interarrival time, indicate a reduction in queue length, their practical impact remains to be validated. Simulations will be presented in following session to confirm our math model.

3.2 Exploratory Analysis

3.2.1 Simulation parameters

Burn-In time Our simulations, conducted with 1000 different seeds, indicate that a 30,000 time unit 'burn-in' period is typically sufficient for system stabilization, as shown in Figure 9. Although there's a slight trend of increase in measurements in the subsequent 10,000 units, the change is negligible.

It's important to note that burn-in times can vary with different simulation parameters. In our case, the 30,000-unit period is a conservative estimate, particularly since other parameters tend to stabilize more quickly. **Simulation time** Given this, we have set our total Simulation time (T) at 200,000 units. While this is less than 10 times the burn-in period — a common rule of thumb — it is considered adequate due to the already generous burn-in duration and the quicker stabilization observed with other parameters.

Number of Simulations

Following thorough testing and calculations, we determined that conducting 1000 simulations for a scenario provides a reliable basis for analysis. With this volume of simulations, the 95% confidence interval range for the system's queue length is approximately 0.03. This narrow range indicates a high level of precision and trustworthiness in our results.

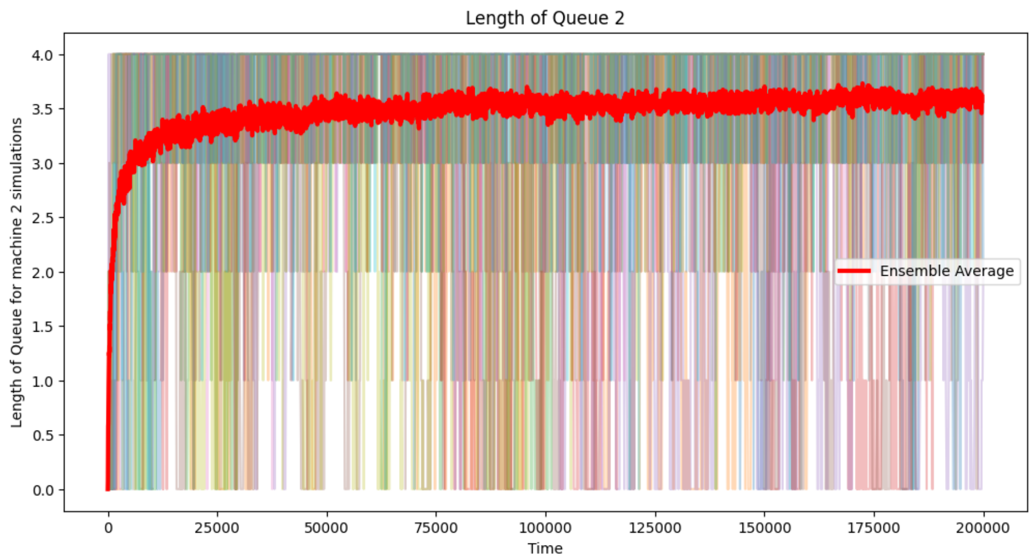

Figure 9: The simulation with original parameter over 1000 seeds for queue length 2, and the ensemle average

3.3 Original system simulation

The simulation results, as illustrated in Figure 9, consistently show the queue length reaching its maximum capacity of 4, indicating a bottleneck in the system. The ensemble average queue length is also observed to be relatively high. Key statistical measures obtained from the simulation are as follows:

- Mean queue length: 3.5364
- Standard Deviation: 0.2454
- 95% Confidence Interval: (3.5212, 3.5516)

These results underscore the **inadequacy** of the queue capacity in the current system configuration, leading to frequent saturation of the queue.

3.4 System Improvement Simulation

We conducted simulations to evaluate various improvements in our system:

- Increase Machine 1's production speed to [23, 21, 19, 17, 12.5] minutes per product.

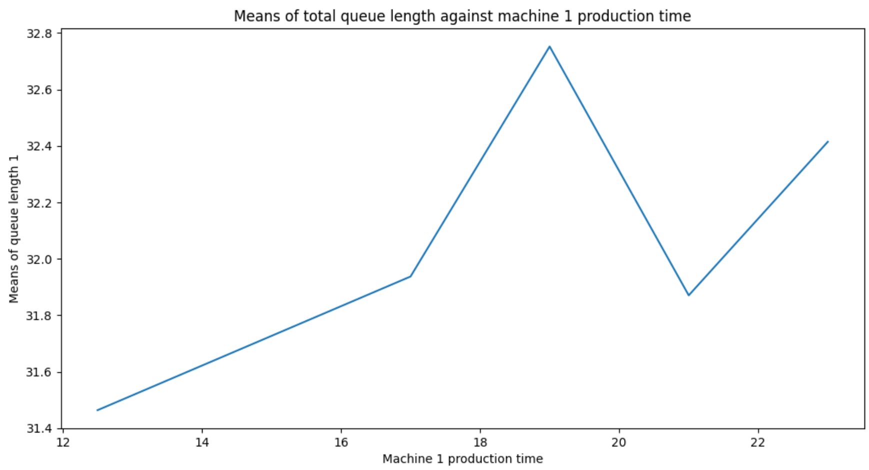

Figure 10: Effect of Machine 1's speed improvement

- Enhance Machine 2's production speed to [55, 50, 45, 29.5] minutes per product.
- Expand Machine 2's queue length to [5, 7, 11, 19].

Despite expert advice against increasing Machine 2's queue length due to cost concerns, we included it for thorough analysis. The effectiveness of these improvements was measured by observing the queue length at Machine 1.

3.4.1 Improving Production Speed of Machine 1

Figure 10 shows that enhancing Machine 1's speed slightly reduces the system queue length, with a marginal decrease from 32.7206 to 31.4634 when production time is halved. Figure 11 further indicates that even at maximum improvement, the reduction in queue length is minimal, suggesting limited impact on overall system efficiency.

3.4.2 Improving Queue Length and Production Speed of Machine 2

Figure 12 demonstrates that increasing Machine 2's queue space from 4 to 19 offers a slight reduction in average queue length from 32.7206 to 31.5583.

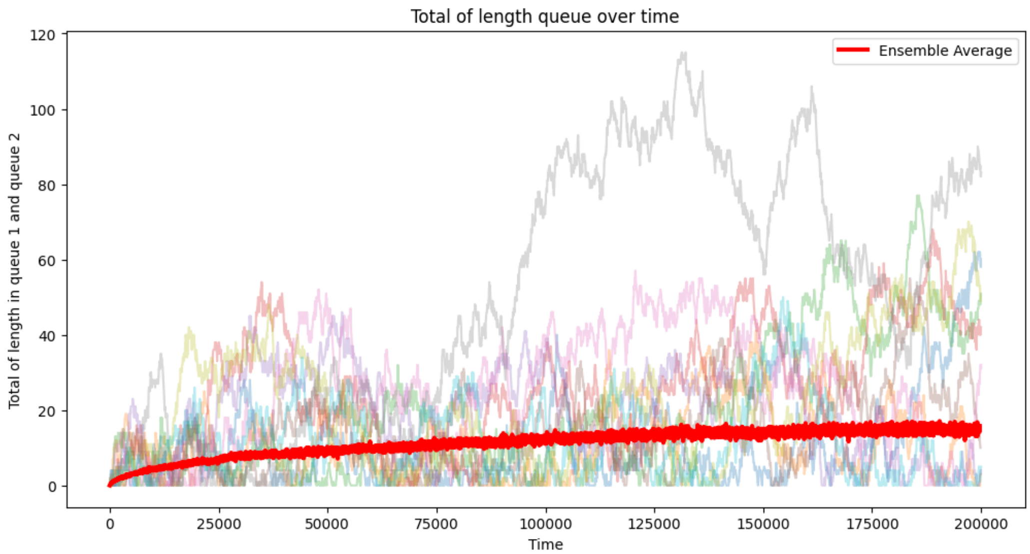

Figure 11: System queue length over time with Machine 1's production time reduced to 12.5 minutes/product

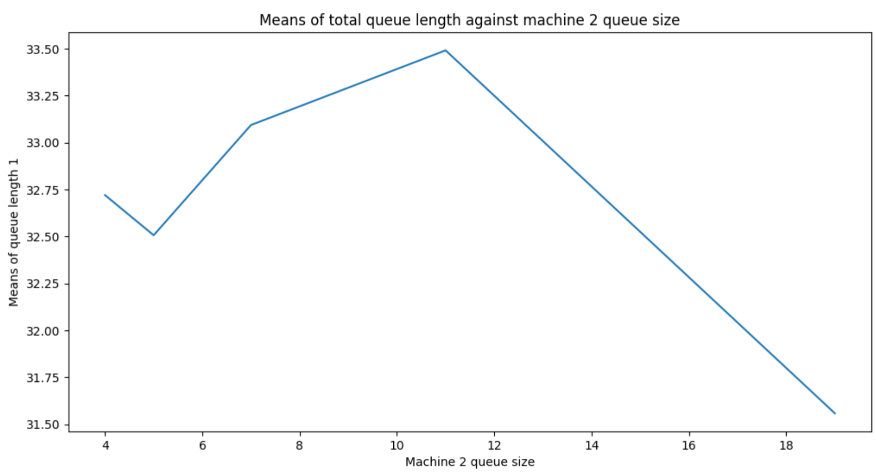

Figure 12: Effect of expanding Machine 2's queue space

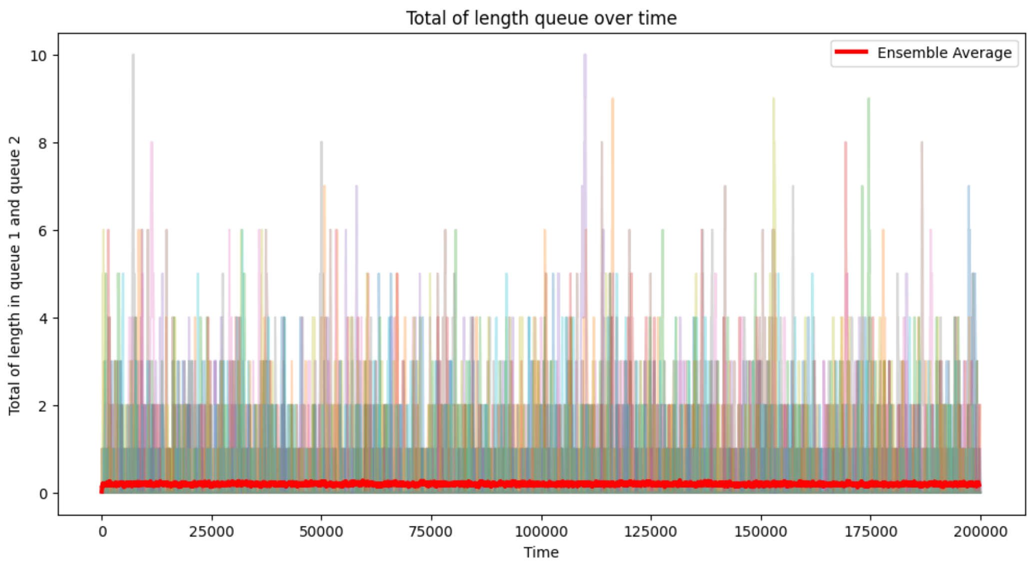

Figure 13: System queue length over time with Machine 2's queue space increased to 19

However, as shown in Figure 13, even with maximum queue expansion, the system still struggles with increasing queue lengths, indicating limited effectiveness.

3.4.3 Effectiveness of Improving Machine 2's Production Speed

Figure 14 highlights a significant improvement in the system's queue length, decreasing dramatically from 32.7206 to 9.6669 with a modest increase in Machine 2's production speed. Further enhancement to 29.5 minutes per product stabilizes the system queue at minimal value of 0.5319, as seen in Figure 15, indicating that the system effectively process new incoming orders.

In conclusion of improvement testing, our best investment is to improving machine 2 production speed.

3.5 Order Increase Simulation

In this simulation, we modeled a 25% increase in order volume by reducing the inter-arrival time from 60 to 48 units, representing a 20% decrease. To assess the system's capacity to handle this surge, we doubled the production

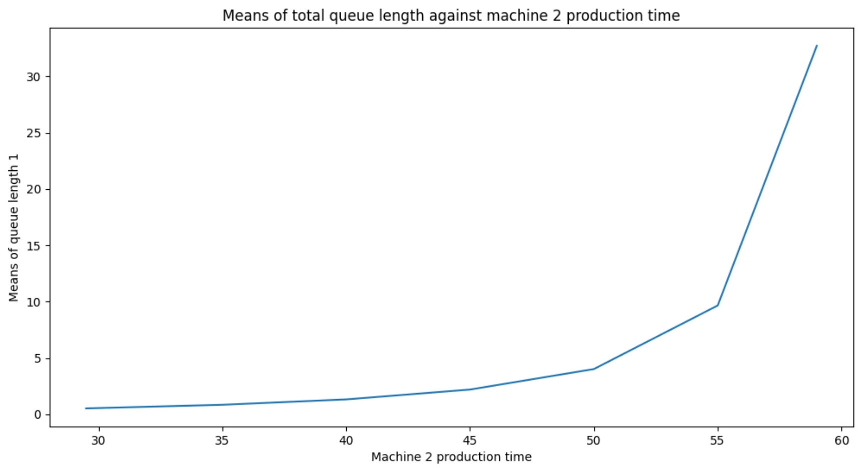

Figure 14: Impact of improving Machine 2's production speed

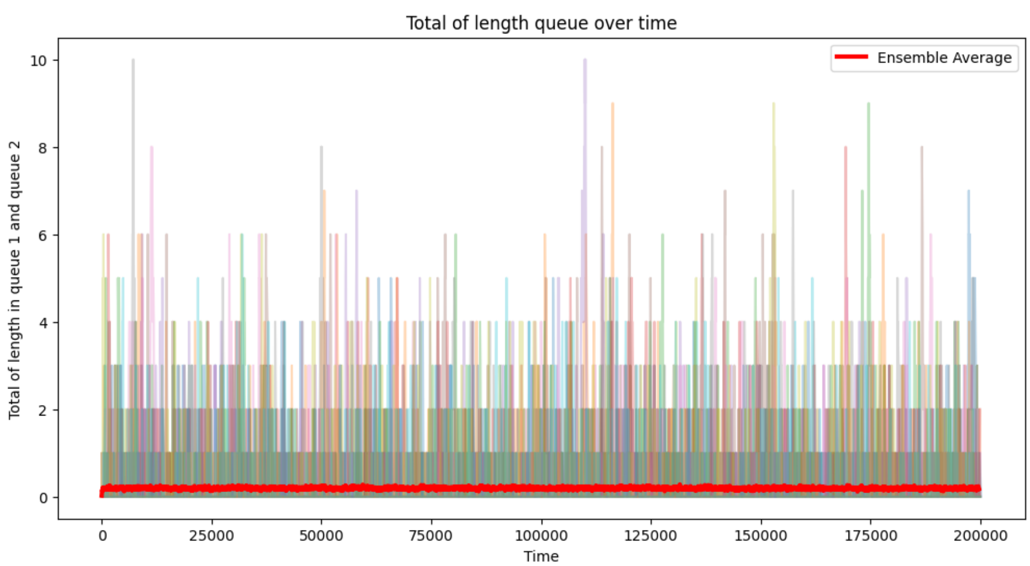

Figure 15: System queue length over time with Machine 2's production time reduced to 29.5 minutes/product

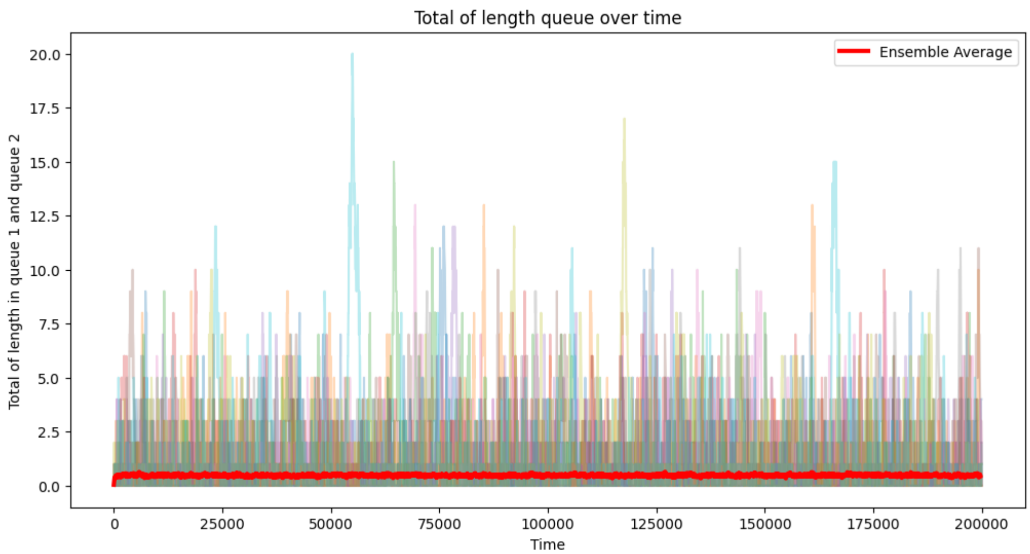

Figure 16: Simulation of a 25% increase in orders with Machine 2's production speed doubled

speed of Machine 2, setting its mean production time to 29.5 units. The results, shown in Figure 16, indicate that the system is more than capable of comfortably dealing with this increased volume of orders. Despite the higher influx, the average queue length at Machine 2 remained low, underlining the effectiveness of the speed enhancement. The detailed statistical measures from the simulation are:

- Mean queue length: 1.0868
- Standard Deviation: 0.1291
- Margin of Error: 0.0080
- 95% Confidence Interval: (1.0788, 1.0948)

These metrics underscore the system's robust performance in managing a 25% increase in order volume, reinforcing the success of the improvements made to Machine 2.

4 Conclusion

Our extensive analysis of Factory X's operations, incorporating simulations and expert advice, was focused on optimizing the efficiency of two critical machines. The findings from the simulations were quite revealing:

1. Machine 2's performance was identified as the main bottleneck in the system. Remarkably, by doubling Machine 2's production speed, the average queue length was significantly reduced from 32.7206 to an impressively low 0.5319, greatly alleviating the system's bottleneck.

2. When simulating a 25% increase in order volume with Machine 2's production speed doubled, the system adeptly managed the higher demand. The average queue length at Machine 2 remained low at 1.0868, showcasing its robustness under increased order pressure.

3. Conversely, enhancements in Machine 1's production speed had a minimal effect. The average queue length decreased only slightly from 32.7206 to 31.4634, indicating that Machine 1 is not the critical factor in the system's overall efficiency.

These insights clearly demonstrate that focusing on enhancing Machine 2's production speed is the most effective strategy for Factory X. This single change not only significantly reduces queue lengths but also improves the overall throughput of the system. While improvements to Machine 1 yield negligible results, optimizing Machine 2's speed is crucial for managing current operations and preparing for potential future increases in order volume.

In conclusion, the primary recommendation for Factory X is to concentrate on boosting Machine 2's production speed. This approach will not only streamline current operations but also equip the factory to efficiently handle potential future increases in demand, ensuring sustainable growth and productivity.