FACTORIFFIC CUSTOM LAMPS

Factory X Production Line Improvements & Impacts of Advertising Campaign on Manufacturing Schedule

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Decision Science Assessment 3: Project Report

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Contents

1 Executive summary

This report addresses the issues at a low-efficient Factory X owned by Factoriffic Custom Lamps, focusing on the production line machine's speed improvement and the performance of responding to the current advertising campaign hosted by the company. The analysis, conducted with the SME (Subject Matter Expert), aims to provide recommendations for Factory X by using simulation to predict the possible outcomes under machine efficiency and order arrival speed increase.

There are two machines in the production line, Machine 1 and Machine 2, and the new arrival order will be queued to be produced in Machine 1 first, which is followed by one more production by Machine 2 again with queues if Machine 2 is not available. The waiting spaces for Machine 1 and Machine 2 are unlimited and four. Specifically, if there are four orders waiting for Machine 2, then the production of Machine 1 has to be suspended until there is available room for the queue.

The simulation with 100 realisations and 2,000,000 minutes is run by Julia and Python, and it solves the three main aspects of the issue. The waiting space of four for Machine 2 is not sufficient since it is common for Machine 1 will stop working. Furthermore, if the speed of Machine 2 increases by a factor of two, then the system will significantly improve and solve the problem of insufficient waiting spaces. Moreover, if the advertising campaign results in a 25% increase in the speed of order arrivals, then it will not affect the efficiency or have any negative impact after the optimisation.

2 Introduction

This report addresses issues on Factory X, an inefficient factory owned by Factoriffic Custom Lamps. It mainly focuses on the improvements of the production line and how the new advertising campaign will impact the manufacturing schedules. All analysis in this report with SME's (Subject Matter Expert) assistance aims to provide Factory X improvement recommendations to adapt to the increasing demand resulting from an upcoming advertising campaign.

There are two machines called Machine 1 and Machine 2 in order in the production line. New orders are queued until Machine 1 is available and re-queued for Machine 2. There is no limit to the length of the queue waiting for Machine 1, but only a maximum of four orders are required for order waiting for Machine 2. Specifically, if the queue for Machine 2 is full (i.e. four waiting orders), Machine 1 must stop working until there is space. All orders processed in Machine 2 will be shipped to the customers.

There are three problems that will be solved in this report. The first consideration is the adequacy of waiting space for lamps being processed in Machine 1 and waiting for Machine 2. Moreover, the simulation will also check if the system will improve if either Machine 1 or Machine 2 efficiency has been enhanced by a factor of two. Furthermore, if the advertising program succeeds, the arrival rate will grow by 25%, outcomes will be predicted, and relevant recommendations will be provided.

3 Background

3.1 Description of System

The overall model is DES (Discrete-Event Simulation) of a production line Machine 1 and Machine 2. There is no limitation for new orders arriving in Factory X, and they will be sent to Machine 1 queuing for production once they arrive. The orders will be queued again for Machine 2 after the production in Machine 1. There is, however, a limitation on the number of orders waiting for Machine 2. The maximum waiting space for Machine 2 is four, which means Machine 1 must stop production once the space is filled. The final step is to send all orders to the corresponding customers after the production of Machine 2.

3.2 Graphs

There are four graphs that will be illustrated in this subsection for a better understanding of this model and system.

Figure 1 is a schematic demonstrating the key elements of this system. All orders will go to the first queue waiting to be produced in Machine 1, but the queue is infinite, which means all new-arrived orders can be queued without limitation. If Machine 1 is free, the order in the first queue will be sent to Machine 1 for production with the FIFO (First-in, First-out) order. The order will be queued again waiting for Machine 2 after Machine 1 production. The queue, however, has a limited waiting space of four. Once the second queue is full (four orders in this queue), Machine 1 has to stop working until the queue has more space to accommodate orders from Machine 1. All orders will be sent to the customers after sending the order to

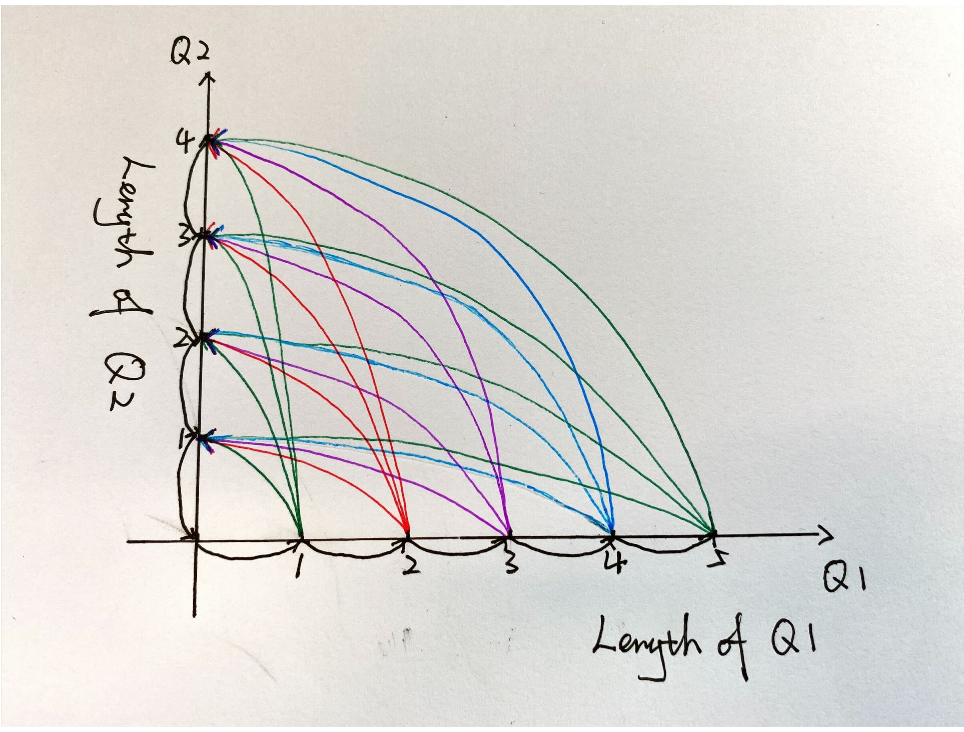

Figure 1: Schematic

Machine 2 with FIFO and production in Machine 2.

Figure 2 displays the process of the production line at Factory X. Other than initialised time and entities, two waiting queues are initialised as empty queues and an arrival event will be added as the first event in the simulation. If the length of the simulation (T) exceeds the setting value, the simulation will be terminated immediately. There are two types of events: Arrival and Finish. When the queue length for Machine 2 is within the limitation, then the whole production line will be analysed from Machine 1. If Machine 1 is free and there is an order waiting in the queue, then the order will be sent to Machine 1 with FIFO (First-in, First-out) ordering and the order will be queued again for Machine 2. Similarly, if Machine 2 is available and there is an order waiting in the queue, then the order will be produced in Machine 2 and finally be sent to customers. However, if the waiting queue for Machine 2 reaches the limitation, then the order in this queue will be moved to Machine 2 once it is free, and the production of Machine 1 will stop until there is room for queue 2, which means all new arrived orders will be queued in the queue 1 and no order is allowed to be sent to Machine 1. This process is implemented by stall function to stall the next event by one.

Figure 3 illustrates how the lengths of queues vary between Machine 1 and Machine 2. All

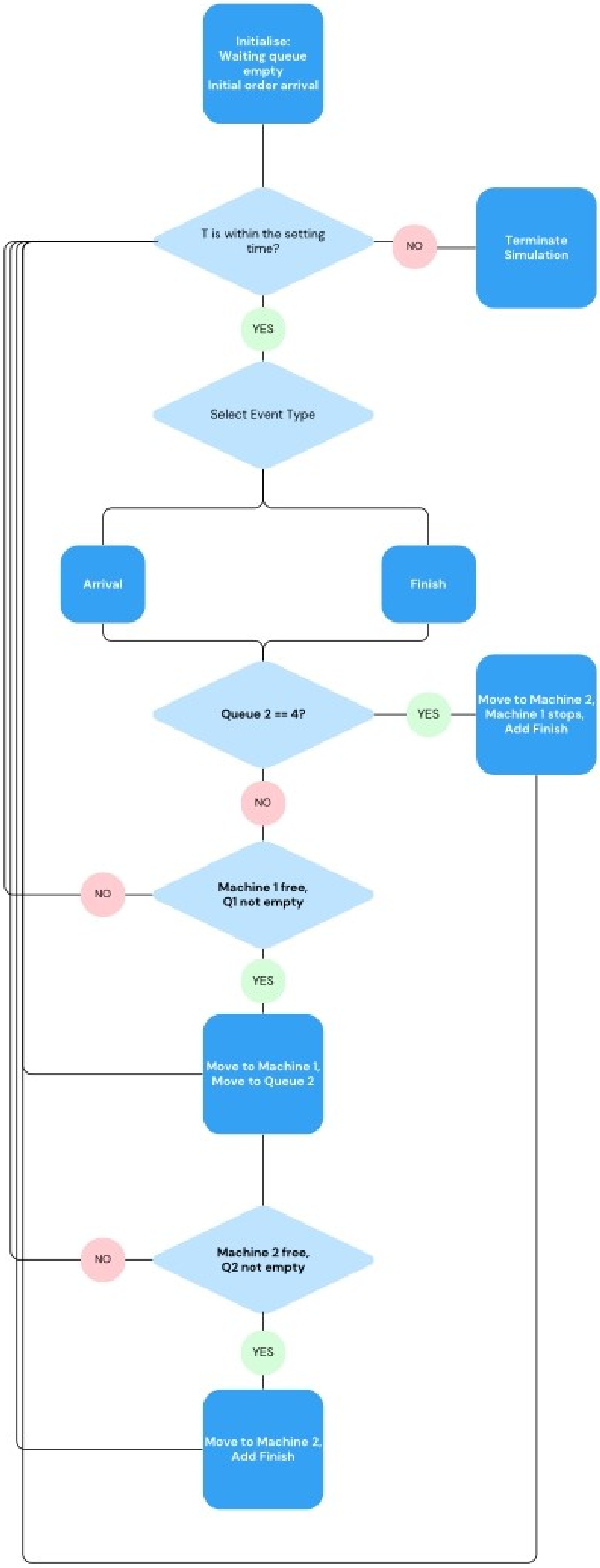

Figure 2: Flow Diagram

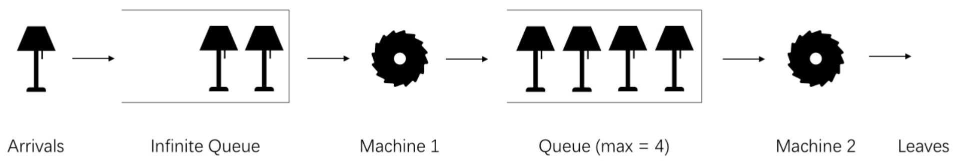

Figure 3: State Transition Diagram

orders will queued in Machine 1 first and there is no limitation on the number of queues for Machine 1. After the production of Machine 1, the order will be sent to the queue for Machine 2, but the maximum waiting space in the queue for Machine 2 is four. During the transition from queue 1 to queue 2, the length of queue 2 can be any length within the limitation. Finally, all orders will depart from the queue for Machine 2.

Figure 4 is the graph showing how all events relate to each other. The initial state is Run, where all queue lengths are zero and two machines are available. When the orders arrive with t_A, the queue length for Machine 1 will increase. Machine 1 will start working when the queue for Machine 1 is not empty and Machine 1 is free. During the production, the queue length for Machine 1 will decrease whereas the Machine 1 in-service will turn to 1. The current event will move to Machine 1 production finish with t_{A1} and shift the Machine 1 working status and increase the queue length for Machine 2. When the queue for Machine 2 is less than four, Machine 1 can keep working. Regarding Machine 2, when the queue for it is not empty and it is available now, Machine 2 can start working with a queue length increase and Machine 2 working status shift. Machine 2 will stop working with time t_{A2} and finish with setting the Machine 2 status as free. When the queue for Machine 2 is not empty, then Machine 2 will continue to produce.

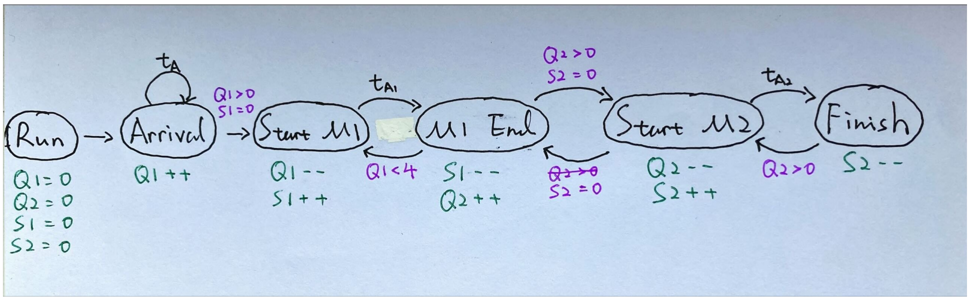

Figure 4: Event Graph

3.3 Modelling Assumptions

This subsection will include all the essential assumptions about the model, which are distributions, random variable independence, queue ordering, waiting spaces and exceptions for priority and preemption. The primary draft code was given by an SME (Subject Matter Expert) the basic assumptions are found based on the code.

In terms of distributions, both inter-arrival time and Machine 2 service time are modelled by the Exponential distribution with mean as the parameter θ. Machine 2 service time is set as consistent during the simulation. Moreover, StableRNG is used for setting variables with random numbers, which can ensure the independence of random variables. Furthermore, Both queues for Machine 1 and Machine 2 are ordered with FIFO (First-in, First-out), where the first order in the queue will be sent to the machine first. Additionally, the initial waiting space for Machine 2 is four, which means there will be at most four orders waiting for Machine 2 after Machine 1. Finally, there will be no priorities and preemption considered in this simulation, and all orders will follow the FIFO principle with no exceptions.

All tests for modelling assumptions will be included in the Methods Section to check if the given background modelling assumption is correct and sensitivity analysis if the assumptions are changed.

4 Methods

There are two main parts which will be discussed in this section, which are verification and validation. Traffic intensity and three verification techniques will be described in the verification section to test the quality of the code. Furthermore, after testing the assumptions, sensitivity analysis will be included to check how sensitive the data is to change the distribution or mean service time of the machine, which is tested by changes in average queue length and if it is within the confidence interval.

4.1 Verification

Two sections of verification will be covered in this subsection, which are the calculation of traffic intensity and three verification techniques, which are unit testing, performance testing and regression testing.

4.1.1 Little's Law

According to the Little's Law, a formula for queuing, the formula is

$$L = \lambda W$$

where L is the average queue length, λ is the arrival rate, and W is the average time in the system. [1]
Based on this formula, the traffic intensity can be calculated as:

$$\rho = \frac{\lambda}{\mu} = \frac{1/1}{60/(25+59)} = \frac{84}{60} = 1.4$$

The traffic intensity is treated than 1, which means the rate of inter-arrival is higher than the order in which leaves the system, so the delay will result in a longer queue.

4.1.2 Unit Testing

Two unit tests are implemented to ensure the proper functioning of the code from SME. The first function is on update function. Time and event were initialised first, and arrival and departure events were pushed manually. After running the update function, there are four updates after the departure event: the event has been removed from the length of the event list; The time has been updated; All lengths of queues and two machines' service statuses are zero; All data are collected and recorded. Therefore, the unit test for the update function is

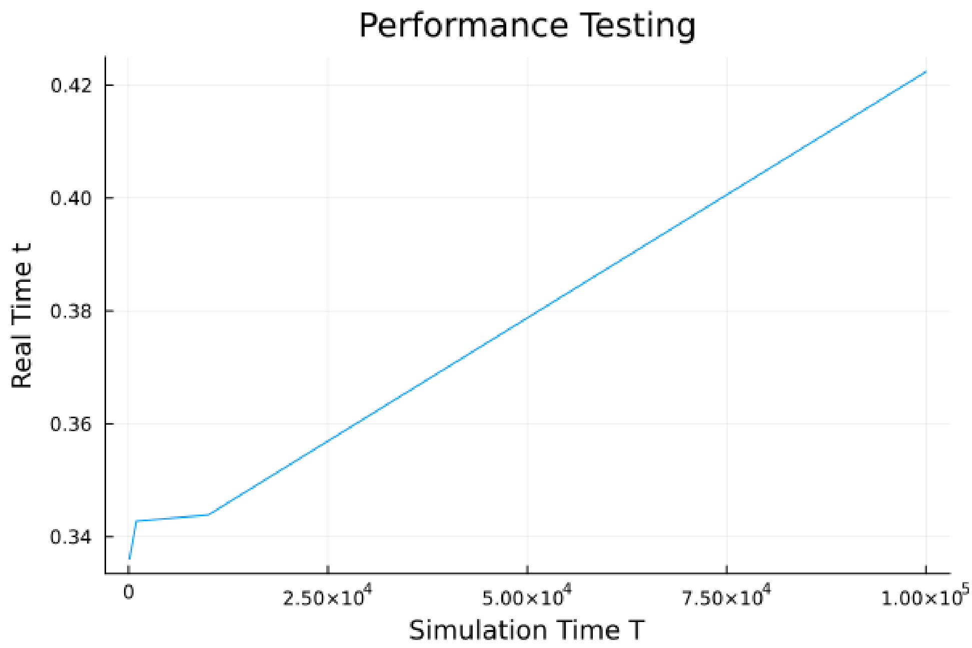

Figure 5: Performance Test

passed.

The second unit test is on the random number generator function, there are three tests used. The first part is to check if the random number generator is within the range, and then to ensure the mean is within the reasonable range (between 0.4 and 0.6 in this test), and the auto-correlation test is used to ensure the independence. All tests are passed, which can also prove the modelling assumption of independence of random variable is appropriate.

4.1.3 Performance Testing

The performance test is used to test the speed of running code. Figure 5 below is the graph demonstrating the relationship between the simulation time and real running time. Specifically, when running the simulation with around 34.7 days (5×10^4 minutes) in real life, it only takes approximately 23 seconds (0.38 minutes) to run it. so it illustrates an efficient performance of the simulation.

4.1.4 Regression Testing

A regression test is also used to ensure if the code is modified, it will not influence the normal running of it. The original code set the expected service time of Machine 1 as consistent, it was changed to Normal distribution to check if the code still works. When modifying the parameters of Normal distribution, μ is the mean service time of Machine 1. The existing data ("measured_times.csv") was read within the code to get an accurate standard deviation σ for parameter setting. Finally, the code still runs properly with the expected file output, a more detailed explanation will be included in the Validation section as sensitivity analysis.

4.2 Validation

After discussion with SME, other than two code files, a csv file is given as the real data which contains the inter-arrival times, Machine 1 and 2 times, it is analysed to test whether the previous assumptions are appropriate. There is one assumption mistake of distribution, but a sensitivity analysis process will be shown below to demonstrate if it will influence the output with different distributions. Other than distribution correction, one more sensitivity analysis will be used to check if changing the mean of Machine 1 service time will influence the output. The theory of sensitivity analysis is that if the average queue length is within the confidence interval of real data, then the sensitivity analysis will pass and there will be no influence on the output after changing the code.

The histograms 6, 7 and 8 below plot the histograms of three lists of variables, and it is easy to find that the overall distribution of inter-arrival time is the same as that of Machine 2 time, which means it is likely that two groups of data can use the same distribution. According to the given assumptions, both inter-arrival time and Machine 2 time are modelled by Exponential distribution.

Figures 9, 10 and 11 below are three QQ plots illustrating if the distributions from the modelling assumption match the real data. It is obvious that all three data match the distributions well. There is, however, a modification in this plot, which is the data of Machine 1 time is modelled using Normal distributions with mean μ and standard deviation σ. The distribution is chosen by Figure 10 below, which demonstrates evenly distributed data with a bell shape, and the graph also confirms the match of Machine 1 time and Normal distribution.

According to the given data, the table 1 demonstrates the 95% confidence interval from the given data and the actual simulation parameters, and all parameters are within the confidence interval, which means they are reasonable. Two sample t-test is replaced here by the confidence interval since it is more apparent to see the differences.

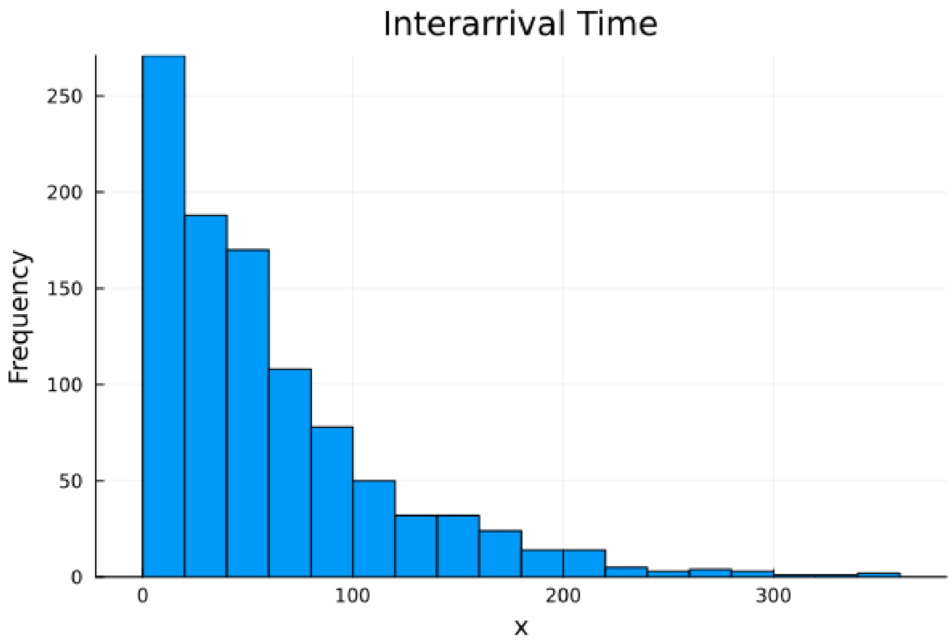

Figure 6: Histogram of Inter-arrival Time

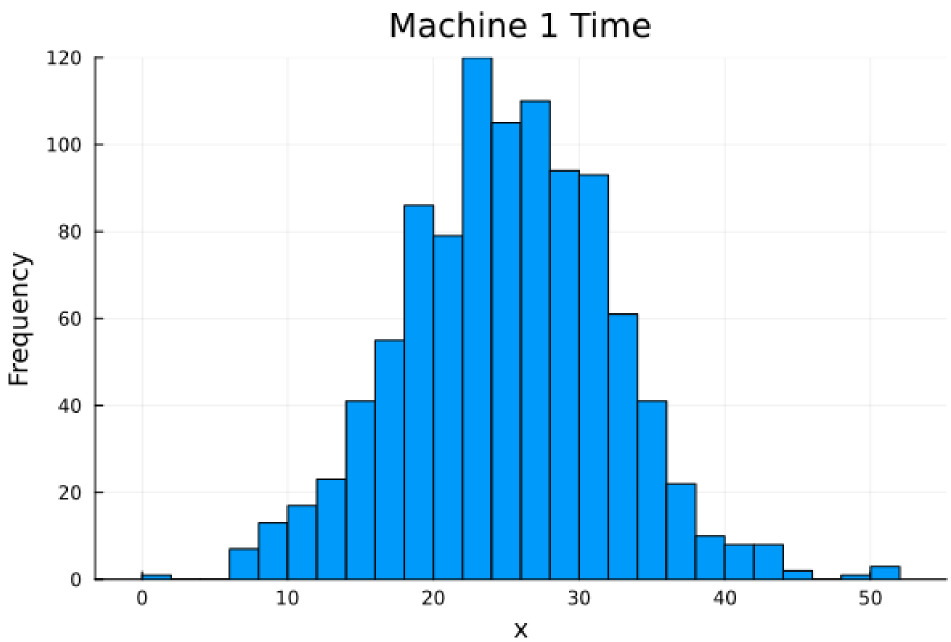

Figure 7: Histogram of Machine 1 Time

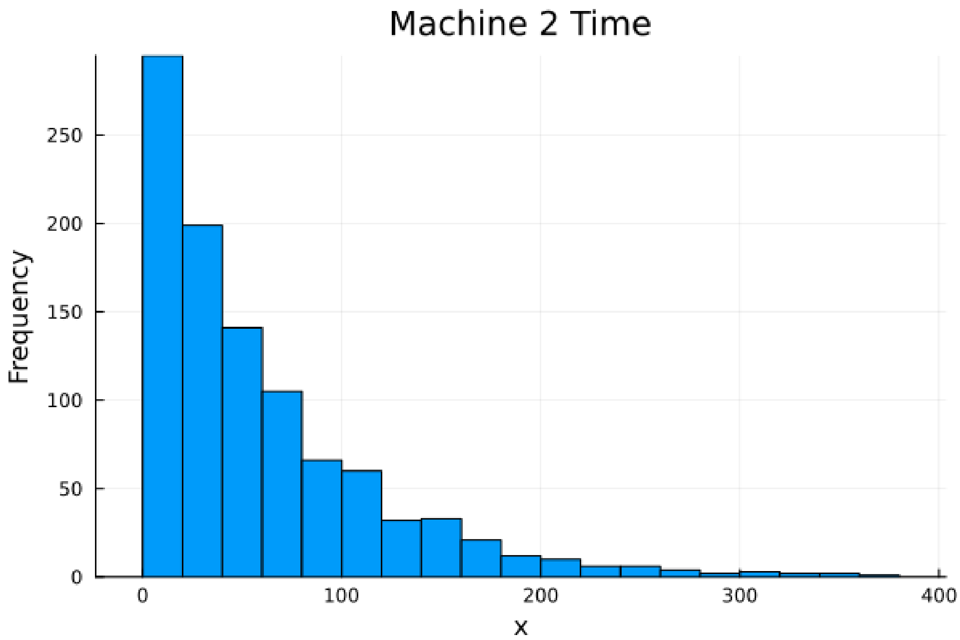

Figure 8: Histogram of Machine 2 Time

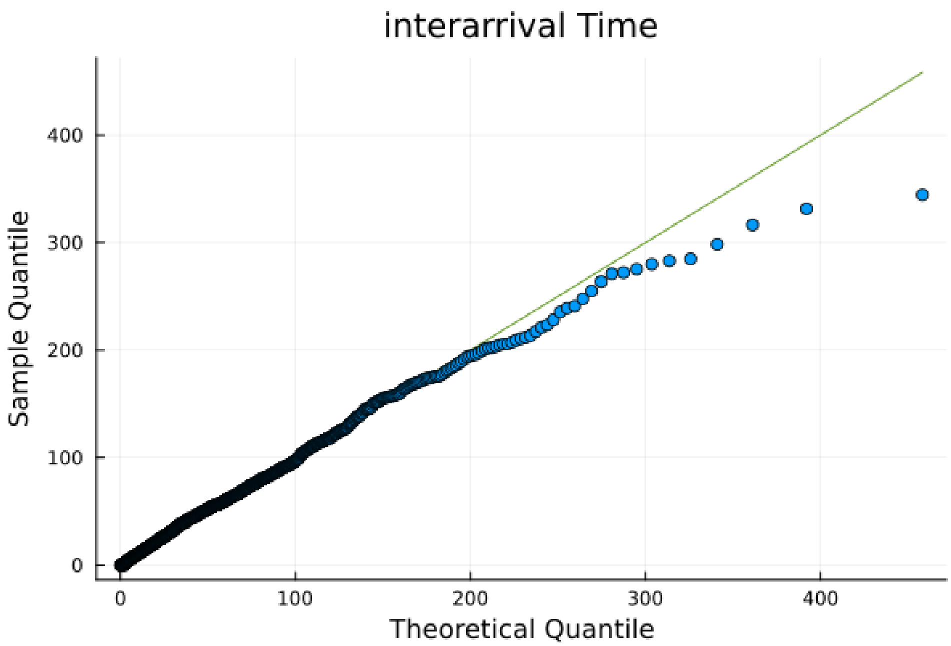

Figure 9: Exponential Distribution of Inter-arrival Time

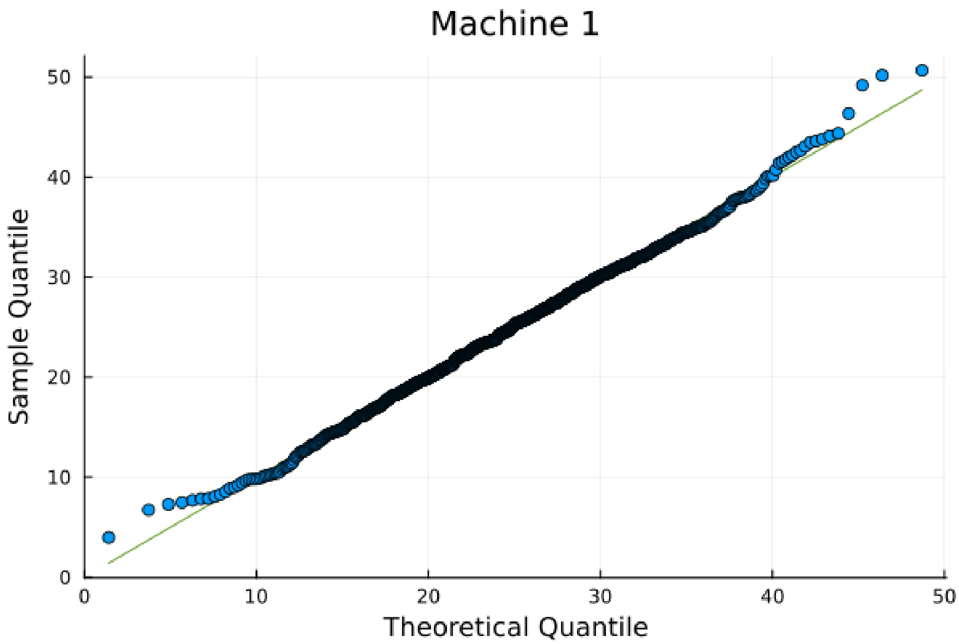

Figure 10: Normal Distribution of Machine 1 Time

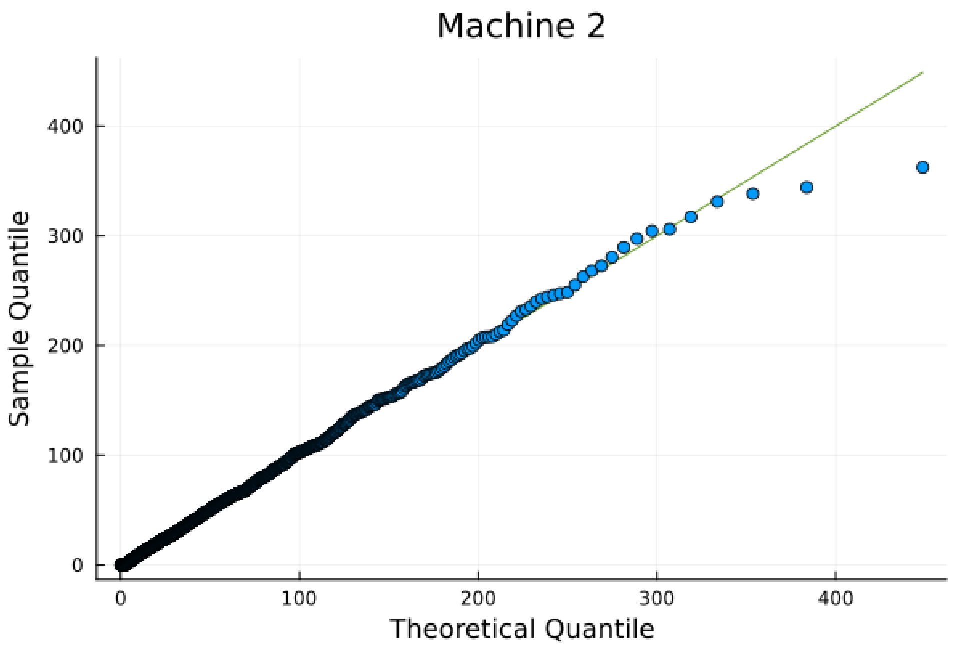

Figure 11: Exponential Distribution of Machine 2 Time

	Lower Bound	Upper Bound	Simulation Data
Inter-Arrival	56.760	63.835	60
Machine 1	24.611	25.501	25
Machine 2	55.325	62.732	59

Table 1: 95% Confidence Interval & Simulation Data

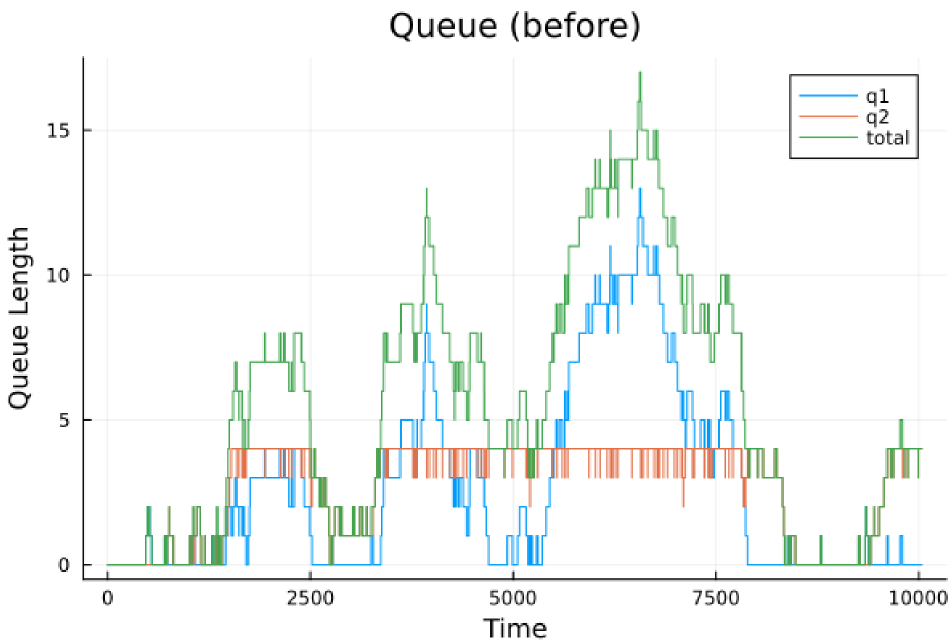

Figure 12: Queue Length for Consistent Time

In terms of the distribution, figure 12 shows the difference queue length for consistent time and 13 illustrates the normal distributed time for Machine 1, which are different. After calculating the average queue length of two conditions, the results are 6.041 and 4.291 for consistent and normally distributed respectively. The confidence interval for average queue length is between 3.836 and 4.282. Although two results are not within the confidence interval, the data normally distributed is closer. Therefore, the distribution of data will influence the sensitivity.

One more sensitivity analysis is on the mean Machine 1 service time change. Based on the table 1, as long as all three types of variables are within the confidence interval, the sensitivity analysis will pass. For example, the simulation with an inter-arrival time be 57, Machine 1 service time be 25.3 and Machine 2 time be 60 will have the same valid simulation as the current simulation.

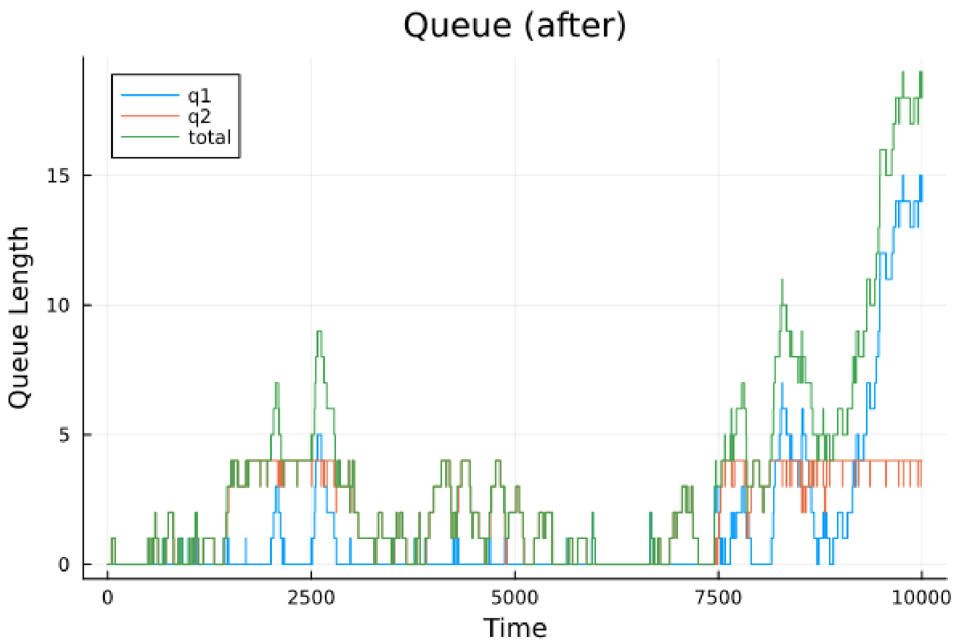

Figure 13: Queue Length for Normal Distributed Time

5 Results

Two main aspects are included in this section, which are exploratory analysis and recommendations of questions of interest. The principle of exploratory analysis is to calculate burn-in time to find the proper number of realisation and simulation length. Furthermore, all the statistical results with burn-in time excluded can be used as a valid support to answer the questions of interest.

After a number of trials with different seeds and times, 100 realisations with a T be 2,000,000 minutes will be used as the final simulation. Here is the comparison of two trials, where the other trial is the simulation with 1000 realisations and 200,000 minutes. Here are the four figures demonstrating the process of burn-in, the reason why the plot and windowed average plot are in different plots is for better visualisation to see the tendency. Figure 14 and 15 are obviously better than Figure 16 and 17 and it is apparent that the tendency of the first trial is more stable than the second trial. Moreover, the overall running time of the first trial is also faster than the second trial, with 161 and 248 seconds to plot the figures respectively. From Figure 15, the trend tends to be stable before 250,000 minutes, so the estimated burn-in time is 200,000 minutes, and the total simulation length is ten times the burn-in time. Therefore, a simulation length of 2,000,000 minutes is considered a reasonable choice with a burn-in time of 200,000 minutes. Finally, all the calculations for the questions

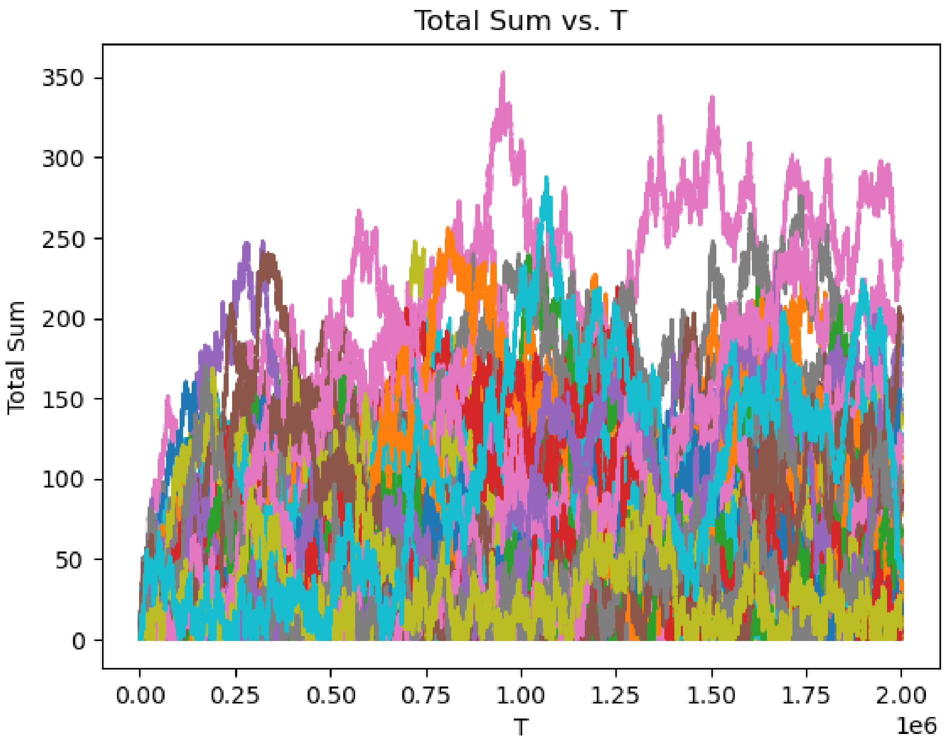

Figure 14: Simulation with seed = 100

will be based on the data without burn-in time.

The first question is whether the waiting space for Machine 2 is sufficient. The average queue length of Machine 2 for the simulation after burn-in time is approximately 3.592, which is close to 4, so the conclusion is that the waiting space of four for Machine 2 is not sufficient and it will cause the queue for Machine 1 to get longer due to the forced suspension of Machine 1.

The second aspect focuses on the improvement of the machine's productivity. Due to the limited funding, only one machine can be more efficient. The average service times of the two machines are 25 and 59 minutes respectively, and the bottleneck of production speed is the limited waiting space for Machine 2, so the better solution is to increase the efficiency of Machine 2 by a factor of 2, and the average queue length for Machine 2 after optimisation is around 0.522, which demonstrates the significant improvement so that Machine 1 will not stop working due to the limited space for Machine 2.

Furthermore, the company's current advertising program is also a factor requiring attention. If the program were to succeed, then the arrival rate of orders would increase by 25%.

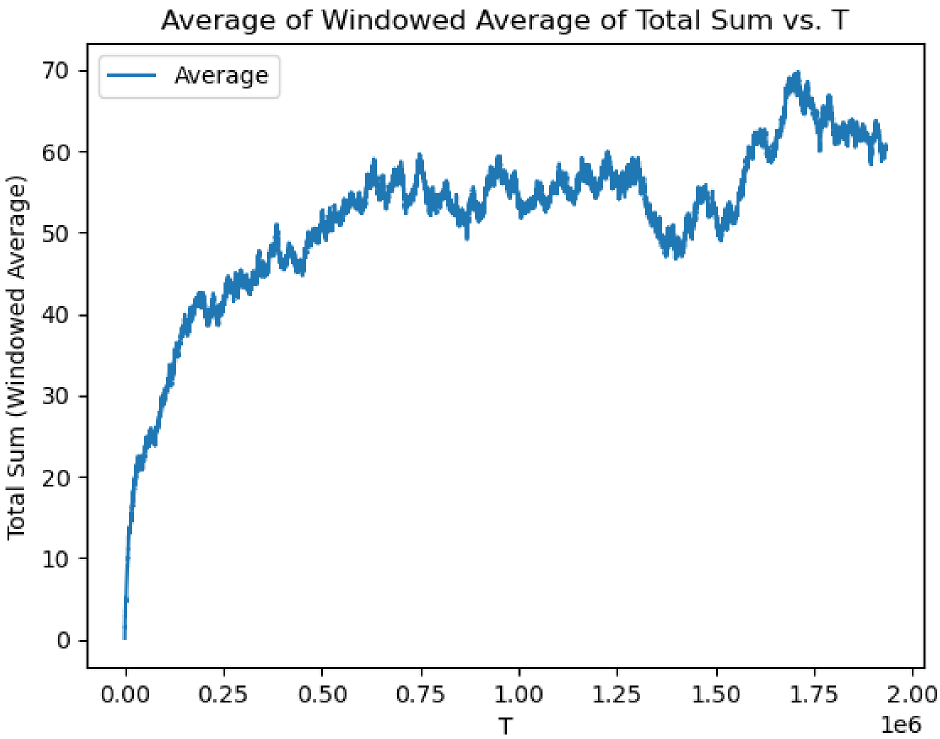

Figure 15: Simulation of Windowed Average with seed = 100

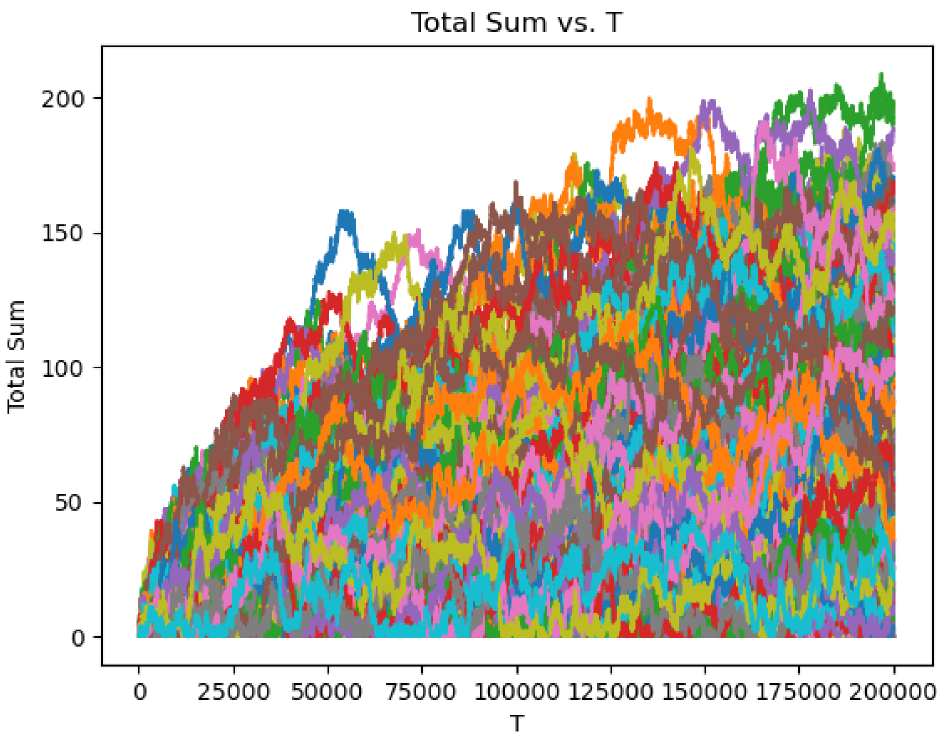

Figure 16: Simulation with seed = 1000

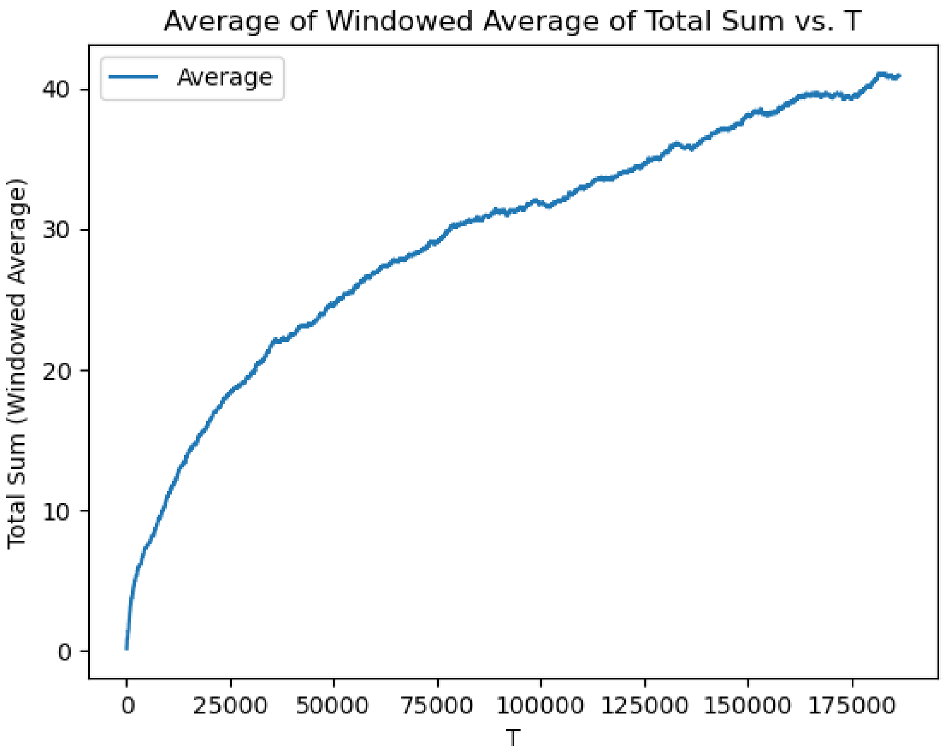

Figure 17: Simulation of Windowed Average with seed = 1000

The average queue lengths for Machine 2 before and after optimisation are about 3.662 and 0.841. It is obvious that Machine 1 will not stop working under the advertising program after the optimisation of Machine 2.

6 Conclusion

In conclusion, the report analyses the relevant aspects of the Factory X production line. Specifically, there are two main aspects of the report, which are the simulation selection and application for prediction.

Both the average inter-arrival rate of order and the Machine 2 service time are modelled by the Exponential distributions whilst the average Machine 1 service time is modelled by Normal distributions. Both sensitivity analysis and the 95% confidence interval are the supportive evidence to ensure the accuracy of the simulation assumption. Specifically, 60, 25 and 59 minutes of inter-arrival, Machine 1 and Machine 2 times are all with the confidence intervals of [56.760,63.835], [24.611, 25.501] and [55.325, 62.732] respectively. Therefore, the fluctuations of parameters within the confidence intervals will all pass the sensitivity analysis.

Furthermore, after a number of trials, the simulation will predict 2,000,000 minutes with 100 realisations using the burn-in principle, and the selected simulation will predict the reasonable recommendations for the questions of interest. The first and foremost concern is that the waiting space of four is not sufficient for Factory X to work normally without any suspension of Machine 1 production since the average queue length for Machine 2 is around 3.592, which is close to the limitation. Furthermore, if the efficiency of Machine 2 increases by a factor of two, then the average queue length will decline from about 3.592 to 0.522 precisely. Moreover, if the advertising campaign were successful, it would bring a 25% boost in order arrivals. Although the average queue length will increase to approximately 0.841, it is still a slight growth compared to the average queue length of 3.662 without optimisation. Therefore, the increased efficiency of Machine 2 has a significant influence on the production line and it can also have the ability to deal with the changes resulting from the advertising campaign.

(Count: 3838 words, 18 figures and table)

References

[1] Little, JDC 1961, 'A Proof for the Queuing Formula: $L = \lambda W$', *Operations Research*, vol. 9, no. 3, pp. 383–387.