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Performance Evaluation of Remanufacturing Systems

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By

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ABSTRACT

Implementation of new environmental legislation and public awareness has increased the responsibility on manufacturers. These responsibilities have forced manufacturers to begin remanufacturing and recycling of their goods after they are disposed or returned by customers. Ever since the introduction of remanufacturing, it has been applied in many industries and sectors. The remanufacturing process involves many uncertainties like time, quantity, and quality of returned products. Returned products are time sensitive products and their value drops with time. Thus, the returned products need to be remanufactured quickly to generate the maximum revenue. Every year millions of electronic products return to the manufacturer. However, only 10% to 20% of the returned products pass through the remanufacturing process, and the remaining products are disposed in the landfills. Uncertainties like failure rate of the servers, buffer capacity and inappropriate preventive maintenance policy would be highly responsible the delays in remanufacturing. In this thesis, a simulation based experimental methodology is used to determine the optimal preventive maintenance frequency and buffer allocation in a remanufacturing line, which will help to reduce the cycle time and increase the profit of the firm. Moreover, an estimated relationship between preventive maintenance frequency and MTBF (Mean Time Between Failure) is presented to determine the best preventive maintenance frequency for any industry. The solution approach is applied to a computer remanufacturing and a cell phone remanufacturing industry. Analysis of variance and regression analysis are performed to denote the influential factors in the remanufacturing line, and optimization is done by using the regression techniques and ANOVA results.

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Chapter- 1: Introduction

The implementation of new rigid environmental legislation and increasing public awareness has forced manufacturers to begin recycling and remanufacturing of their used products, when they are thrown away by customers. Remanufacturing is an industrial process to restore used products to new conditions. Remanufacturing is defined as “the process of restoring a non-functional, discarded product to like-new condition” (Lund, 2012). Thus, one can achieve the quality standards of a new product with the used parts. Moreover, it reduces the consumption of untapped resources by reusing the old materials. Also, recycling of the product gives us an option to recover some material from the old part and we can use this material to in making of new products.

The remanufacturing process starts with the collection of the used products. To get the used products, there is some collection cost, which is paid by the remanufacturer to get back the product. After the collection of the returned products, the next challenge is to sort them into distinct categories like reusable (good), remanufacture (moderate) and recycle (bad). A product will pass through operations like disassembly, cleaning, inspection, repairing, reassembling, and quality testing to get the remanufactured product. Typically, bad quality products are recycled after reliability testing and inspection. Recycling is not only a good way to earn profit; it also preserves the raw material in the earth’s crust. It is not necessary to recycle all the parts during the remanufacturing process, one can also recycle unusable parts and the remaining parts can be used to replace the parts in other products. A detailed remanufacturing process is shown in Figure 1.

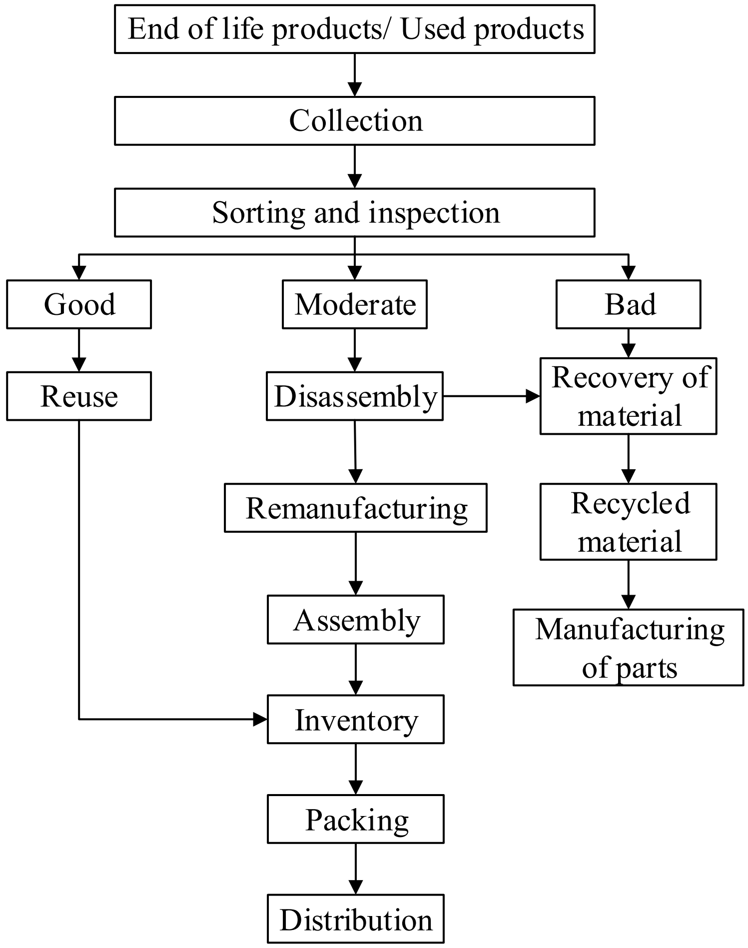

Figure 1: Detailed reverse logistic process

One should face certain problems while remanufacturing the product. One of the biggest problems is that the products are time sensitive in the remanufacturing industry and the value of the used products is continuously decreasing with time. Delay in remanufacturing will lower the selling price of the product. Simultaneously, the profit of the firm will drop. Many electronic products have short life cycles and their value goes down very quickly after a certain age. Thus, the products with short life cycles need to be remanufactured as fast as possible to get the maximum revenue from remanufacturing. Moreover, delay can also affect the choice of the customer while buying products, and the products with short life cycle are less likely to be sold. Research shows that remanufactured products generally lose 30% of their value in delay (Guide et al., 2006). Higher congestion levels at the remanufacturing facility can also result in loss of value for time sensitive products.

Figure 2 shows the revenue generated from various remanufacturing processes. One can notice that if the value of the returned products is $1000, then one can recover only $550 from various remanufacturing processes. Products lose the 45% of the value due to the delays in the remanufacturing process. The time value of the product drops as time passes, and once the product reaches the end of its life cycle, recycling or scrap is the only way to generate revenue.

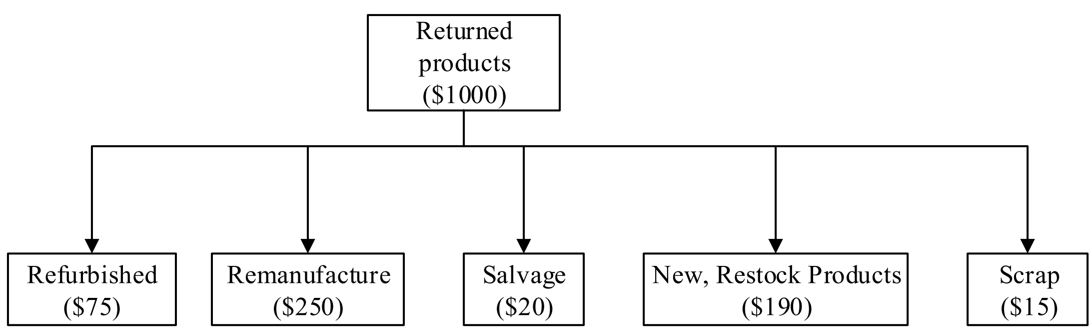

Figure 2: Revenue generated from various remanufacturing processes

Adapted from Blackburn et al., 2004

Figure 3 depicts the volume of the products in the market with the time. From the figure, it is clearly seen that once the product is collected and sorted then it passes through the remanufacturing. The figure shows that how much value of the product is lowered due to delay in the remanufacturing. Blackburn et al., (2004) analyzed that only 20% of returned products are reusable and remaining 80% products need to be fixed by performing the remanufacturing operations. Once a product reaches to the end of life cycle, the value of the product plummets very quickly. Time sensitive products such as PCs, laptops may lose 1% of its value per week and the rate is increased at the end of the life cycle. At this rate, price of the returned products may go down 10% to 20% during evaluation and remanufacturing process.

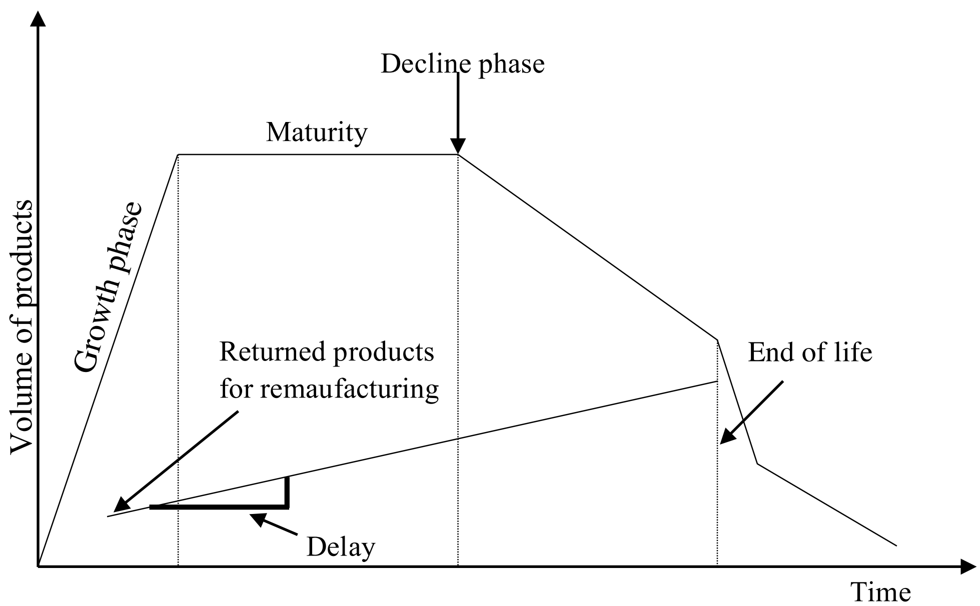

Figure 3: Time value of returned products

From Figure 2 and Figure 3, one can say that there is a significant amount of decrement in revenue due to delay. The main reason for delay in remanufacturing is uncertainty. Two types of uncertainties are related to delay in remanufacturing. The first type of uncertainty is external uncertainty. External factors like different lead times, uncertain quality and quantity of the products in remanufacturing, and level of demand are responsible for interruption in the remanufacturing process. The second type of uncertainty is internal uncertainty. It occurs due to interruption on the work floor. Factors such as accidental failures of the machines (Deput et al., 2007), improper buffer allocation (Guide, 1996), high congestion at the facility, and higher yield defect rates are blamable for delay in the remanufacturing process. If the industry has higher congestion and longer delay in remanufacturing then it is better to sell the products at the salvage value (Guide et al., 2009).

The external uncertainty is difficult to control as it is based on customers and the efficiency of the supply process. The collection and distribution process can be accelerated by increasing the number of facilities in the area. Nonetheless, one should consider the return rate of the product and the quality of the product before opening new facilities. Thus, the external uncertainty is very complex to control. However, the internal uncertainty can be controlled by finding the optimal configuration of the production line. One of the main reasons for slowing down the remanufacturing process is an accidental failure of a machine. The reduction in the failure rate can be achieved by implementing the proper preventive maintenance policy. Therefore, preventive maintenance can be a vital factor to increase the production of a remanufacturing line. Different ways to improve the output of a remanufacturing line are listed below:

1. Allocation of buffer capacity in the production line (Buzacott, 1971), which will allow the production line to continue work when one of the machine is down.
2. Improve the availability of machines by providing the parallel machines, where appropriate in the production line.
3. Increase the capacity of the machines.
4. Apply preventive maintenance in the production line, which will help to increase production by restoring reliability.

From the discussed ways, the second way is to increase the availability of the machine by providing the parallel machine. Hence, industries must increase the number of machines in the production line. This could be costly for small production firms and a big plant size is needed to implement this strategy. Another way to increase production is by increasing the capacity of the machine. But, this cannot be improved easily. However, the buffer capacity and the maintenance policy are two factors of every production line that can boost the production rate very easily.

The production rate of any remanufacturing line is highly influenced by its buffer allocation. Furthermore, the cost of the production line also varies due to different buffer allocations. If the buffer has a small capacity, then it will lower the production rate. Higher buffer capacity will lead to higher cost and it consumes more space on the floor. There is an optimal buffer allocation for every production line. Increment in the capacity of the buffer beyond that level, then it may decrease the production rate with a higher level of work-in-process inventory. Blocking and starvation are two basic phenomena, that take place in the production unit due to the buffer capacity. When a machine wants to discharge its finished part into the downstream buffer and the buffer is filled to its maximum capacity, then the machine cannot discharge the part and it must wait until the space becomes available. This situation is called as blocking, as the machine cannot start the processing with another part.

When a machine finishes the process on a part, it wants to start the work on the new workpiece. If the upstream buffer is empty, then the machine cannot start processing because of the unavailability of the workpiece. This situation is known as starvation. The blocking and starvation make the machine idle and the idle state of the machine can decrease the overall production. The lower production rate also represents delay in the remanufacturing line. Thus, production lines need optimal buffer allocation to increase the production rate and decrease the cost of the buffer.

Another parameter that influences the production rate is an accidental failure of a machine. One must perform corrective maintenance to repair a randomly failed machine. Corrective maintenance is a time consuming and costly process. Sometimes, it is necessary to replace the worn part to get the machine back in running condition. Due to the longer repairing times, it also affects the other machines of the production line. If buffers have enough inventory, then machines can continue the production. Otherwise, machines must wait until the failed machine will get repaired. The accidental failure is highly responsible for lower production rate and poor product quality. Accidental failures reduce the reliability of the machine and reduction in reliability decreases the quality of the workpiece (Koren et al., 1998).

One of the best ways to reduce random failure of a machine is to use preventive maintenance in the remanufacturing system. Preventive maintenance helps to restore the reliability level of the machine. A machine with higher reliability has higher availability.

Different policies of preventive maintenance have a fluctuating effect on the production rate. If machines have very frequent maintenance, then it will decrease the accidental failure and production rate. The less frequent preventive maintenance can have more failures and higher cost. Thus, it is necessary to find the optimal preventive maintenance strategy to accelerate production. Generally, preventive maintenance action includes things like changing oil, cleaning, and checking of other production equipment.

The combination of the buffer allocation and preventive maintenance can lift the production rate with lower cost. The aim of this thesis is to find the optimal buffer allocation and preventive maintenance strategy, which will increase the production rate of the remanufacturing line and lower the cost of the production unit. The thesis will focus on the following areas:

- To apply the hypothetical relationship between MTBF and preventive maintenance action to decide the best preventive maintenance frequency to maximize the availability of the machine.
- To find the effect of processing multiple products in the remanufacturing line and how different processing rates of different products will affect the production rate and capacity of the buffer.
- To study the influence of different buffer allocation on five-machine and nine-machine production lines.
- To investigate the various levels of preventive maintenance and their impact on the cycle time and cost of the system.

- To find the optimal cycle time and cost of the remanufacturing line by finding the optimal combination of buffer allocation and preventive maintenance strategy by reducing the experiment size.

The remainder of the thesis is organized as follows: Chapter 2 gives a review of research papers related to the remanufacturing and buffer allocation problem, multi products, and buffer allocation, preventive maintenance strategy and buffer allocation methods. Chapter 3 presents the notations, working assumptions, and parameters used in this thesis. Chapter 4 shows the methodology used to create the simulation model of a five machine and four-buffer remanufacturing system. It also illustrates the calculations of preventive maintenance time and MTBF and discusses experimental design creation. Analysis of a five machine and four-buffer production line is presented in Chapter 5. Analysis of variance (ANOVA) is applied to understand the effect of the different factors on the production output. Results and factors are explained in Chapter 6 which have been calculated in Chapter 5. Finally, conclusions and recommendations for future research are presented in Chapter 7.

Chapter – 2: Literature review

This chapter of the thesis will present the literature and the concepts related to this research. A thorough review of the literature is conducted to get the necessary knowledge and to find out the problem in previous published works. The following topics are briefly studied in the literature to understand the solution approaches in published works:

1. Remanufacturing and buffer allocation
2. Multi-product production line with buffer allocation
3. Preventive maintenance along with buffer allocation
4. Methodology

The published works are analyzed to have a clear idea about previous works and the methods that have been used. The literature regarding each issue is given below under the problem title.

2.1 Remanufacturing and buffer allocation:

The growing need of remanufacturing has caught the attention of many manufacturers. Remanufacturing is not only an effective way to reduce the waste, it also reduces the consumption of virgin resources. Moreover, remanufacturing provides the quality and functionality of new products with used parts. Thus, it reduces the consumption of virgin resources. Remanufacturing can be profitable as one can generate good revenue by recycling and remanufacturing used parts. One of the major problems is buffer allocation in a remanufacturing line. Buffer allocation has a significant impact on the production rate. Few researchers have explored buffer allocation problem in the remanufacturing line.

Firstly, the buffer allocation issue in remanufacturing line was analyzed by the Aksoy & Gupta, (2005). The authors addressed the buffer allocation problem in the remanufacturing cell, which has finite buffer capacities, and unreliable servers. The processing times, failure rates, and repair rates are exponentially distributed in their model. They suggest a heuristic algorithm to achieve the optimal buffer allocation with the goal of cost optimization in the production line. An efficient algorithm was presented by Aksoy & Gupta, (2010) to find the optimal buffer allocation in the remanufacturing line. In this research, they consider the N-policy for the servers. That means the server will start working on secondary work when they do not have enough products in the inventory. They analyzed the system by using the expansion method and the system was tested for balanced and unbalanced line conditions.

Aksoy & Gupta (2011) studied the methodology to optimize the buffer allocation in the transfer line. In the case study, they assumed that the first server never gets starved and the last server will not be blocked during the production period. They propose a heuristic algorithm to find the optimal buffer allocation when servers are on vacation. Machines will start to work on secondary parts when the server is on vacation. The goal of the research is to minimize the cost of the system. Su & Xu (2014) presented a buffer allocation problem for the hybrid production line, which follows the N-policy. They used the improved decomposition principle and expansion method to find the throughput of the system. The goal of the research is to minimize the cost along with the buffer capacity. The sorting of the products was done by the quality of returned products.

2.2 Multi-product and buffer allocation:

Generally, production lines are dedicated to produce the one product type. However, when the quantity of the workpieces is highly uncertain then industries should process the multiple products in the production line. Industries have faced many problems while they are processing multiple products. One of the major problems is setting up of the machines. The setup of the machines is required as per product type changes, and it may be time-consuming. The second problem is the capacity of the buffer. With the change in product type, processing time also changes and it influences the buffer allocation. A very small number of published works is available which show the buffer allocation problem in the context of multiple products.

This issue was firstly investigated by Abdul-Kader & Gharbi (2002). They developed a simulation-based methodology to find the relationship between the different buffer capacities and the cycle time of the production line. They found that how the various levels of buffer capacity can affect the output of the production line. Moreover, the cycle time for each machine was calculated to discover the bottleneck machine in the production line.

A non-linear mathematical programming model indicated by Abdul-Kader et al., (2011), which was used to evaluate the impact of the different buffer capacities on a serial production line which is processing the multiple products. The objectives like minimizing the makespan, minimizing buffer size, and maximizing the output of the system were used to evaluate the performance of the system. A lexicographic goal programming method was used to optimize the multiple objectives. In their case study, they used the unreliable machines. Instead of using failure and repair rates in the mathematical model, they incorporated the effect of the failure in their model to measure the performance.

2.3 Preventive maintenance and buffer allocation:

Generally speaking, all the machines are subjected to the random failures in a production line, which negatively affects the production rate of the system. One of the best way to reduce the random failure is the introduction of preventive maintenance in the production line. Many papers are published to find the optimal preventive maintenance for a production line. A methodology to find the optimal preventive maintenance for two machine production line was represented by Van der Duyn Schouten & Vanneste (1995). They calculated the time to decide the preventive maintenance frequency by considering the age of the machine. They found the optimal age for a machine to perform the maintenance action.

A simulation based methodology was proposed by Noseworthy & Abdul-Kader (2004) to determine the effect of periodic preventive maintenance on production cost and production output. They used a hypothetical relationship between Mean Time To Failure and preventive maintenance to find the frequency of preventive maintenance. Chelbi and Aït-Kadi (2004) analyzed the single machine production line, which should feed another production unit with a constant rate. They developed a mathematical model to determine the optimal JIT inventory and period of preventive maintenance to optimize the overall cost of the system. Chelbi & Rezg, (2006) considered a periodic preventive maintenance strategy based on the age of the equipment. They applied the preventive maintenance by determining the optimal age of the machine and JIT inventory stock by following the minimum availability level of the system.

Rezg et al.,(2005) presented a methodology to find the optimal JIT inventory and preventive maintenance frequency by using simulation model and experimental methodology. Meller & Kim (1996) applied an analytical method to study the impact of preventive maintenance on two machine and one buffer production line. In their case study, they considered the various processing times to analyze the effect of different processing times and preventive maintenance on the performance of the system. Zequeira et al., (2004) determined the optimal length of continuous production periods between maintenance actions to find the optimal buffer inventory. They build the buffer stock at the beginning of the production period to supply the products when the machine is down for repair. Zequeira et al.,(2008) defined a mathematical model to find the optimal buffer inventory. They used a heuristic method to achieve the optimal cost and buffer inventory in the production line.

In another study ,Radhoui et al.,(2010) proposed a strategy which was characterized by two decision variables: the rate of nonconforming units on the basis of which preventive maintenance actions should be performed, and the size of the buffer stock to be built in order to palliate perturbations caused by stopping production and performing maintenance actions of random durations. The proposed modeling approach combined simulation, experimental design and regression analysis to provide an estimate of the cost function that included quality, maintenance and inventory cost. Zandieh et al.,(2017) proposed a genetic algorithm to determine the optimal buffer allocation and period of preventive maintenance. They used the normal distribution to represent the preventive maintenance in the production line. The goal of this paper was to increase the production rate and minimize the defective rate of products.

2.4 Methodology:

2.4.1 Analysis of Transfer Lines Consisting of Two Unreliable Machines with Random Processing Times and Finite Storage Buffers (Gershwin & Berman, 1981)

Introduction:

A Markov chain model was illustrated in the paper for the two machine and one buffer production line. The buffer has a finite capacity and it was assumed that the buffer is reliable. The machines have different statistical distribution to understand its random behavior. The processing times, failure and repair processes have exponential distribution for the presented case study. The Markov model depicts the presentation of the discrete part. The model is analyzed and the compact solution was obtained to investigate the limiting behavior of the production line.

Strength of the paper:

The Markov chain model was calculated for the two machine and one buffer model having the buffer capacity of 3. This simple production line has 16 distinct states to measure the performance of the system. Steady state probability was calculated to measure the performance such as machine efficiency, overall output, and average work in process inventory. The model has a unique way to define the failure probability. The probability of a machine to fail was dependent on the operation time. Any machine with the long operation time is more likely to breakdown. Such assumptions of operation-dependent failure can be seen in the real manufacturing lines.

Limitation of the paper:

Markov chain is one of the most useful analytical method to analyze and design the serial production line. Markov chain models have two major limitations. One limitation is the large state space and the second is that the Markov chain models are not decomposable. The number of distinct states of a Markov chain is the product of number of different machine states and the number of distinct buffer levels. The number of distinct states can be calculated by the equation 1, where D represents the buffer capacity in the equation 1.

$$Number\ of\ states = 2^{m} \sum_{i=0}^{m-1} (Di + 1) \qquad (1)$$

We need to calculate 6.24×10^{24} distinct states to analyze the production line of 20 machines and 19 buffers, where each buffer has capacity of 10.

Conclusion:

Markov chain models can be easily implemented for the smaller production line to measure the performance of the production line. The number of distinct states increases exponentially as the number of machines, number of buffers and buffer capacities increase within the production line.

2.4.2 Modelling and analysis of three stage transfer line with unreliable machines and finite buffers (Gershwin & Schick, 1983)

Introduction:

In an important class of manufacturing systems, products sequentially move from one machine to another and rest in buffers between two stations. A Markov chain is used to model the production line with the unreliable machines. Different states of the Markov chain represent the different operating condition of the workstations and level of material in the buffer. Steady-state probabilities are sought to achieve the relationship between the different parameters of transfer line and performance measures such as production output, and work in process. An algorithm was suggested to solve the large-scale structured Markov chain problems by reducing the matrix size.

Strength of the paper:

To find the steady-state probability distribution of M- state Markov chain, it is necessary to solve a set of M linear transitions (equations) with M unknowns. Conversely, M is a huge number to track and solve the system. They suggested a methodology to find the l vectors which satisfy the at least M-l transition equations. Since l is much smaller than M, it is very easy to solve them. In the three-machine line $M = 8(N_1 + 1)(N_2 + 1)$ (where N_i is the capacity of buffer i) and $l = 4(N_1 + N_2) - 10$. Clearly, when N_1 and N_2 are large, 1 is much smaller than M. All the matrix of internal states, transition matrix, and vector matrix are defined separately. If one wants to measure the performance of any section then users do not need to calculate the probability of each state.

Limitation of the paper:

Some difficulties were encountered while solving the three-machine production line. Vector matrix size is much smaller than the transition matrix though as the buffer size increases, it increases the number of distinct states. Generally, the nullity of the vector matrix is 1. Some numerical experimentation has indicated that due to larger buffer sizes, the nullity of vector matrix becomes larger than the 1. Any numerical technique is likely to fail as the buffer size increases in the production line. As the buffer size increases, the vector matrix becomes close to the numerical singularity. The authors ran into some numerical problems regarding the boundary condition as the buffer size increases. The Markov chain model cannot explain the blocking and starvation phenomena.

Conclusion:

The proposed methodology was only reliable for the smaller production line, which has two machines. As the number of machines increases in the production line, the number of states to analyze the production line also increases. During the numerical calculations, the authors ran into some problems regarding the nullity of the matrix and numerical singularity. Any numerical technique is not able to solve the vector matrix as the buffer size in production line increases.

2.4.3 An efficient decomposition method for the approximate evaluation of tandem queues with finite storage space and blocking (Gershwin, 1987)

Introduction:

This paper illustrates an approximation methodology to evaluate the performance of transfer line where phenomena like starvation and blocking are very important to understand. This kind of system is very hard to analyze as it has a large state space and it is very hard to decompose this type of system. The decomposition method is illustrated in the paper to find conservation of flow in the system. The authors decomposed the K machine production line into K-1 two machine lines. Thus, the output of the first two machines becomes the input for the downstream machines. The decomposition of five machine and four buffer production system is illustrated in Figure 4:

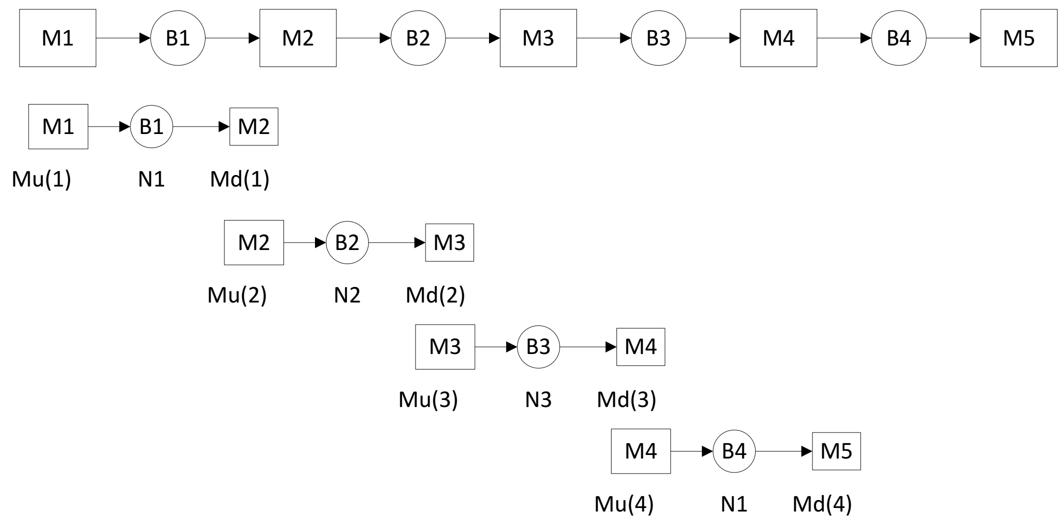

Figure 4: Decomposition method

Strength of the paper:

The proposed algorithm needs 88 evaluations to analyze the performance of the three machine and two buffer production line. The time required to solve these 88 evaluations is less than the exact mathematical model such as the Markov chain model. The results of approximate methods are extremely close to the results obtained by solving the Markov chain model. The measured error in production rate was less than 0.02% and the error in the average buffer level was less than 2.6%. The buffer levels were little larger than the Markov chain model. The results were also compared with the simulation results and the error was very small between the approximation method and the simulation.

Limitation of the paper:

The number of evaluations increases with the increase in the length of the production line. The number of evaluations can be represented by $0(k)^3$, where k is the number of machines. The algorithm generates nearly 1000 equations to approximate the output of the eight machine of the production line. Exact methods are not available for longer production line or for the large buffer capacities. Thus, we cannot validate the results of the approximate method. The author established the equations related to conservation of flow, flow rate idle time relationship, starvation of machine, and failure of the machine. Nevertheless, due to the limitations of the method, the algorithm failed to solve the equations. In addition, the processing and repair times were deterministic. The accuracy of the approximation method has not been analyzed for any statistical distribution.

Conclusion:

The approximate methodology is accurate to analyze small production lines. The number of evaluations increases with the increase in the number of machines and the results of the longer production lines cannot be validated as the exact solutions are not available for the long production systems. These results can be compared with the simulation results for validation purposes. Therefore, it is better to use the simulation as it is faster and more economical way for the analysis and it is the only way to get the standardize results for the longer production line.

2.4.4 A robust decomposition method for the analysis of production lines with unreliable machines and finite buffers (Le Bihan & Dallery,2000)

Introduction:

This paper presents a decomposition method for the analysis of a production line composed of unreliable machines and finite buffers. All the machines of the production line have deterministic processing times. Moreover, all the machines have same processing time in the production line. They have presented a better approximation methodology, which is based on a better approximation of the repair time distribution. This method uses a three-moment approximation of the repair time distributions of the equivalent machines. An algorithm is presented to evaluate the performance of the production line. A case study has been done on the ten machine and nine buffer production line. Results of the proposed methodology are compared with the simulation results and Generalized exponential (GE) method to find the accuracy of the new method.

Strength of the paper:

They have proposed a hyper-exponential distribution for the repair time. Repair time has two different values. Both the repair times have a different probability of taking place whenever a machine will go under failure. They have generated separate equations to find out the efficiency of the downstream and upstream machines. However, the efficiency of the line is dependent on the working time of the downstream machine, which can help to calculate the overall efficiency of the production line easily. Moreover, to calculate the three-moment hyper-exponential distribution, they have separate equations to measure the machine performance under each moment. The proposed methodology is very fast compared to the previously presented decomposition method of Gershwin (1987). Also, the results have shown the least error compare to the other approximation methods. Their method has average 2% error compare to the simulation results.

Limitation of the paper:

After comparing the simulation results and hyper-exponential method results, I noticed that the overall output has 2% error than simulation results and the error in average buffer level is always higher for the buffers which have large capacities. Error in average buffer level increases with the increase in buffer size. From the different scenarios, the largest measured error for buffer level was 12.30% when the buffer capacity is increased from 50 to 100. Thus, the hyper-exponential method cannot be useful when we have higher buffer capacities. Moreover, deterministic and similar processing time is also one of the problem as most of the production lines have variable processing time in the production line.

Conclusion:

The hyper-exponential methodology is faster compared to the generalized exponential and exponential method. In addition, it is very accurate as compared to the previous methods. This method showed higher errors in buffer levels when they increased the buffer capacities in the production line. Hence, it cannot give an accurate buffer size for a production line and we cannot get the optimum configuration of the production line.

2.4.5 A decomposition method for approximate evaluation of continuous flow multi-stage lines with general Markovian machines (Colledani & Gershwin,2011)

Introduction:

A decomposition method for evaluating the performance of continuous flow lines with unreliable machines and finite capacity buffers. This study uses the exact solution of general two-stage Markov model as the base of the calculations. Different decomposition equations are generated to investigate the partial and complete blocking and starvation phenomenon in the system. Moreover, a decomposition algorithm has been developed to solve the equations of the decomposition and the results are compared with the existing decomposition methods and simulation for different production lines having different number of machines and different layouts.

Strength of the paper:

A methodology has been presented to measure the partial and complete blocking and starvation phenomenon in the production line along with the output and buffer level. They followed the similar decomposition method to evaluate the production line. They divided the production line into n-1 subsystems. As we know, the Markov chain is limited to only two-machine production line with small buffer sizes. They used Markov chain to evaluate the performance of the two-machine production line after using the decomposition rule. Furthermore, they have separate equations to measure the partial and complete blocking and starvation. They have developed the equation to measure the probability of being in partial or complete blocking state. The time spent in these two states was found and then the sum of these two states was used to find the overall condition of the production line during the production period. As we know, Markov chain model is very accurate to measure the performance of the production line and the use of this method to measure the longer production line gives the better results than the previous methods.

Limitation of the paper:

The proposed methodology is more accurate than the previous methods but the time taken to evaluate the performance of one sub-system is little higher than the decomposition method and it does represent the results for the random processing times. All cases represent the deterministic processing times while repair and failure times have different distribution to check the accuracy of the proposed methodology. The error in the output was less than 1% in all cases still the error in buffer level was high. The biggest error measured was 4% in the buffer level. Buffer space is related to the cost of the system and output of the system. Therefore, if we are looking for the economical and faster configuration of the production line then we need to look for accurate buffer levels.

Conclusion:

The decomposition method with the Markovian model is very accurate to measure the output of the different system. The error is small in the production output but the error in buffer level was little higher. Moreover, the proposed methodology has not been analyzed for larger buffer spaces. Moreover, the accuracy of the model is not analyzed when we have higher buffer capacities. Thus, we cannot apply this methodology to the longer production lines, which have higher buffer capacities. In addition, the accuracy of results for such a system will play a key role to apply this methodology to different lines. Thus, this method can be used for some production line but simulation could be faster and easier to measure the performance of the system under different kind of uncertainties.

2.5 Gap in literature:

By examining the existing literature, Aksoy & Gupta (2005) and Aksoy & Gupta (2010) have explored the buffer allocation problem in remanufacturing industry. The main drawback of their research is that their methodology is highly dependent on the reusable rate of the returned product. If the reusable rate is low then they cannot get the higher output and revenue. Thus, their methodology cannot be applied to the remanufacturing line to understand the effect of the buffer on work floor. Moreover, they did not find the optimal buffer allocation for the intermediate buffers in the production line. They found the optimal buffer allocation for a remanufacturing cell. Thus, it can be useful to develop optimal inventory level in the plant. Moreover, maintenance strategy and its effects are not analyzed in remanufacturing line yet.

Scant literature is available for multiproduct production lines. Abdul-Kader et al., (2011) found the optimal buffer allocation by using the lexicographic goal programming method but their model does not explain the effect of failure and repair rate in the production line. They just added the effect of failure in the model but any addition of such effect can not represent the real problem in the unreliable production line.

Many papers are published to understand the influence of buffer allocation and preventive maintenance policy on the production line. Chelbi & Rezg, (2006); Rezg et al., (2005); Zequeira et al., (2008) created the methodology to find the optimal preventive maintenance frequency and buffer inventory. Nevertheless, their research did not focus on the buffer allocation problem in the production line. Their research goal was to determine the optimal JIT inventory to continue the production during maintenance actions. Additionally, their methodology does not explain the change in failure rate when we introduce the preventive maintenance in the production line. If we change the frequency of the preventive maintenance then will it increase or decrease the MTBF of a machine. These published works do not elucidate the change in MTBF due to different preventive maintenance actions.

Different mathematical models are presented in the literature, which are used to evaluate the performance of a manufacturing system. However, Markov chain is the only method, which gives the exact performance of the system by mathematical calculation, and it is limited to only two-machine production line. Approximate analytical methods can be used to get the performance of longer production line. Nevertheless, approximation methods have higher variation in the average buffer level and a minor error in the output of the system. In addition, mathematical methods are a little bit slow compared to simulation modeling methods. Therefore, this research will use the simulation method to get better and complete results.

A simulation-based experimental methodology is applied in this thesis to understand the effect of different buffer allocation and preventive maintenance frequencies on the remanufacturing line. The performance of the production line is measured in terms of the cycle time and profit of the firm. Experimental methodology is useful to understand the impact of each factor on the performance of the system and to obtain the optimal value of the different factors by ANOVA. Besides, simulation methodology will also generate useful statistics like machine downtime, blocking time, the percentage of starvation, and many other parameters, which can be valuable to understand the performance of the remanufacturing line. This simulation approach will help to analyze and design the real-world remanufacturing line. Table 1 represents the summary of the literature review.

Table 1: Summary of literature review

Author	Year	Manufacturing	Remanufacturin	Multi-product	Cost Minimize	Production Max.	Reliable system	Unreliable sys.	Buffer Optimize	Preventive maintenance	Methodology
Aksoy & Gupta	2005		✓		✓			✓	✓		Heuristic algorithm
Aksoy & Gupta	2010		✓		✓	✓	✓		✓		Expansion Method
Aksoy & Gupta	2011		✓		✓			✓			Heuristic Algorithm
Su & Xu	2014	✓	✓		✓	✓		✓	✓		Expansion method

Table 1: Summary of literature review, cont'd

Author	Year	Manufacturing	Remanufacturin	Multi-product	Cost Minimize	Production Max.	Reliable system	Unreliable sys.	Buffer Optimize	Preventive maintenance	Methodology
Abdul-Kader & Gharbi	2002	✓		✓		✓		✓	✓		Simulation
Abdul-Kader, Ganjavi, & Baki	2011	✓		✓		✓	✓		✓		Lexicographic goal programming
Vander duyn Schouten & Vanneste	1995	✓				✓		✓	✓	Based on age of the machine	Mathematical model
Steven & Abdul-Kader	2004	✓				✓		✓		Periodic	Simulation

Table 1: Summary of literature review, cont'd

Author	Year	Manufacturing	Remanufacturin	Multi-product	Cost Minimize	Production Max.	Reliable system	Unreliable sys.	Buffer Optimize	Preventive maintenance	Methodology
Chelbi & Ait Kadi	2006	✓			✓			✓	✓	Periodic	Analytical model
Chelbi & Rezg	2006	✓						✓	✓	Based on age of the machine	Mathematical model
Chelbi, Rezg & Xie	2005	✓						✓	✓	Based on age of the machine	Simulation & experimental design
Meller & Kim	1996	✓						✓		Periodic	Analytical model
Zaqueira, Valdes, & Berenguer	2004	✓			✓			✓		By optimal length of production period	Mathematical model

Table 1: Summary of literature review, cont'd

Author	Year	Manufacturing	Remanufacturin	Multi-product	Cost Minimize	Production Max.	Reliable system	Unreliable sys.	Buffer Optimize	Preventive maintenance	Methodology
Zaqueira, Valdes, & Berenguer	2008	✓			✓			✓	✓	Periodic	Heuristic method
Radhoui, Rezg & Chelbi	2010	✓			✓			✓	✓	By rate of nonconforming units	Simulation & experimental design
Zandieh, Joreir-Ahmadi & Fadaei-Rafsanjani	2017	✓				✓		✓	✓	Periodic	Genetic Algorithm
Present research	2017		✓	✓	✓	✓		✓	✓	Periodic	Simulation & experimental design

Chapter -3: Problem notation and working assumptions

This chapter of thesis presents the notations, statements of the experiments, various performance measures and different cost factors that are relevant to the simulation study during the experiments.

3.1 Notations:

The following symbols are used in this thesis. The machines of the serial production line are represented by M_i, where i=1, 2…n. The intermediate buffers are represented by B_i, where i=1, 2…n-1. Products are represented by P_j, where j = 1,2…m. During the case study, the basic parameters, which are used continuously, are as follow:

P_i = processing time of machine M_i

S_i = Setup time of the machine M_i

$MTTR_i$ = mean time to repair for machine M_i

$MTBF_i$ = Mean time between failure for machine M_i

μ_i = Mean repair rate of machine M_i

λ_i = Mean failure rate of machine M_i

During the study, the failure rate and repair rate are intended by following equations:

$$\lambda = \frac{1}{MTBF}; \qquad \textbf{(2)}$$

And

$$\mu = \frac{1}{MTTR} \qquad \textbf{(3)}$$

In this research, all the buffers are assumed reliable and they have finite capacity. Symbols related to the buffers and preventive maintenance are as follow:

D_i = Maximum capacity of buffer B_i

PM = Preventive maintenance

CM = Corrective maintenance

T = Clock time

T_i = Time for the preventive maintenance

3.2 Working Assumptions:

The assumptions considered while simulating the model of the serial production line of five machines and four buffers is as follows:

1. There is a continuous supply of raw material to the first machine consequently, the first machine never gets starved. In addition, the last machine of the production line has an infinite capacity buffer and consequently, all finished parts can exit the system. Hence, the last machine never gets blocked.

2. Two different types of products are produced in the production line. Another product starts processing when the defined lot of the prior product finishes its production. After processing a lot of a product, a machine needs to setup before processing another product. The processing sequence of all the product on any machine is always the same, i.e. product 1, product 2…., product j.

3. All the machines of the serial production line can process only one work piece at a time.

4. All the transitional buffers have finite capacity. The maximum available capacity of a buffer is C_i.

5. All the workstations are prone to unplanned breakdown. The failure rate is defined by λ_i. The random failure of a machine is usage or operation dependent. This means that if the machine is idle, then it cannot breakdown.

6. The transferring time of parts from one machine to buffer and from buffer to another machine is negligible. Even the loading and unloading of a product on a machine is negligible.

7. All the buffers are reliable buffers. They are not subjected to the random failure and repairs.

8. Corrective maintenance and preventive maintenance workers are always available. Corrective maintenance is performed based on of first down – first repair for any machine.

9. Preventive maintenance frequency is predefined in the program. A machine undergoes a maintenance action for the expressed time based on scheduled time.

3.3 Performance Measures:

To measure the performance of the remanufacturing system, various parameters are modeled in the simulation model. The utmost significant parameters that have been used in this study are as follow:

PO = Total production output for the serial production line

CT = Cycle time to finish the production of the product mix

BC_i = Average contents in buffer

BT_i = Total time machine is blocked

IT_i = Total time a machine is idle

MDi = machine downtime

TCM_i = Total corrective maintenance time during a simulation period

TPM_i = Total preventive maintenance time during a simulation period

BF_i = Total time when the buffer is full

TBA_i = Total time when buffer is half full

BF_i represents the total time when a buffer is full. This parameter helps to calculate the possibility that how long a buffer will be full. The higher the time a buffer is full, the more it increases the total blocking time in the system. Same way, TBA_i is helpful to find the time in which a buffer is available. If the buffer is partially full more often, then it will reduce the frequency of interruptions in production due to blocking. These parameters are used in the thesis to evaluate the cycle time, total cost of the system and are used in the experimental design.

3.4 Cost parameters for analysis of total cost:

The following parameters are used in the thesis to calculate the operating costs, maintenance cost and total cost.

C_r = Cost of corrective maintenance or cost of unscheduled repair

C_p = Cost of preventive maintenance or cost of scheduled repair

C_B = Operation cost of buffer

C_w = Cost of workers to operate the production line

C_h = Inventory holding cost

C_u = Cost of utility to operate the plant

C_e = Cost of equipment and building

C_c = Cost of product collection

TC = Total cost of the production system to operate for the defined period

The cost of the corrective maintenance (C_r) depicts the cost to repair the machine when it fails accidentally. It consists of the various costs like cost of labor, downtime cost, and the maintenance cost to repair the machine. Preventive maintenance is used to reduce the accidental failure and the cost of preventive maintenance is represented by C_p. Preventive maintenance action includes the cost of oil change, cleaning, inspection, labor, and coolant. The buffer operating cost (C_B) represents the cost of storing the inventory in buffer (Meller & Kim, 1996). The inventory holding cost (C_h) is the cost to store and handle the inventory in storage. Utility cost (C_u) includes electricity cost and general maintenance cost for the plant. The cost of equipment and building (C_e) represents the cost associated with insurance, fire protection, taxes, building rental, and machine depreciation cost (Li et al.,2008).

Chapter – 4: Methodology

This chapter of the thesis presents the methodology used to analyze the serial production line using simulation-modeling technique, to perform the mixed level fractional factorial design and the way to calculate the preventive maintenance frequency and MTBF for different intervals of preventive maintenance.

4.1 Description of simulation model:

Figure 5 illustrates the flow of parts in multi-stage serial production line. The flow chart illustration follows the notation of Section 3.1. In a multi-stage serial production line, each part or raw material arrives in the storage. The storage has infinite capacity, and in the multiproduct production line, all the products arrive at the defined arrival time. As the simulation starts, first product j will move to the machine 1 and at same time all the machines will go under the setup downtime. When the setup is done, a part will move to machine M_1 if the machine is available to accept the part.

The availability of the machine depends on whether the machine is processing another part, has failed, or is under preventive maintenance. If the machine is in failed condition then the machine will be repaired by corrective maintenance and machine downtime will be noted. If it is time to perform the PM then it will perform the preventive maintenance and after the maintenance action and will start the processing of the part.

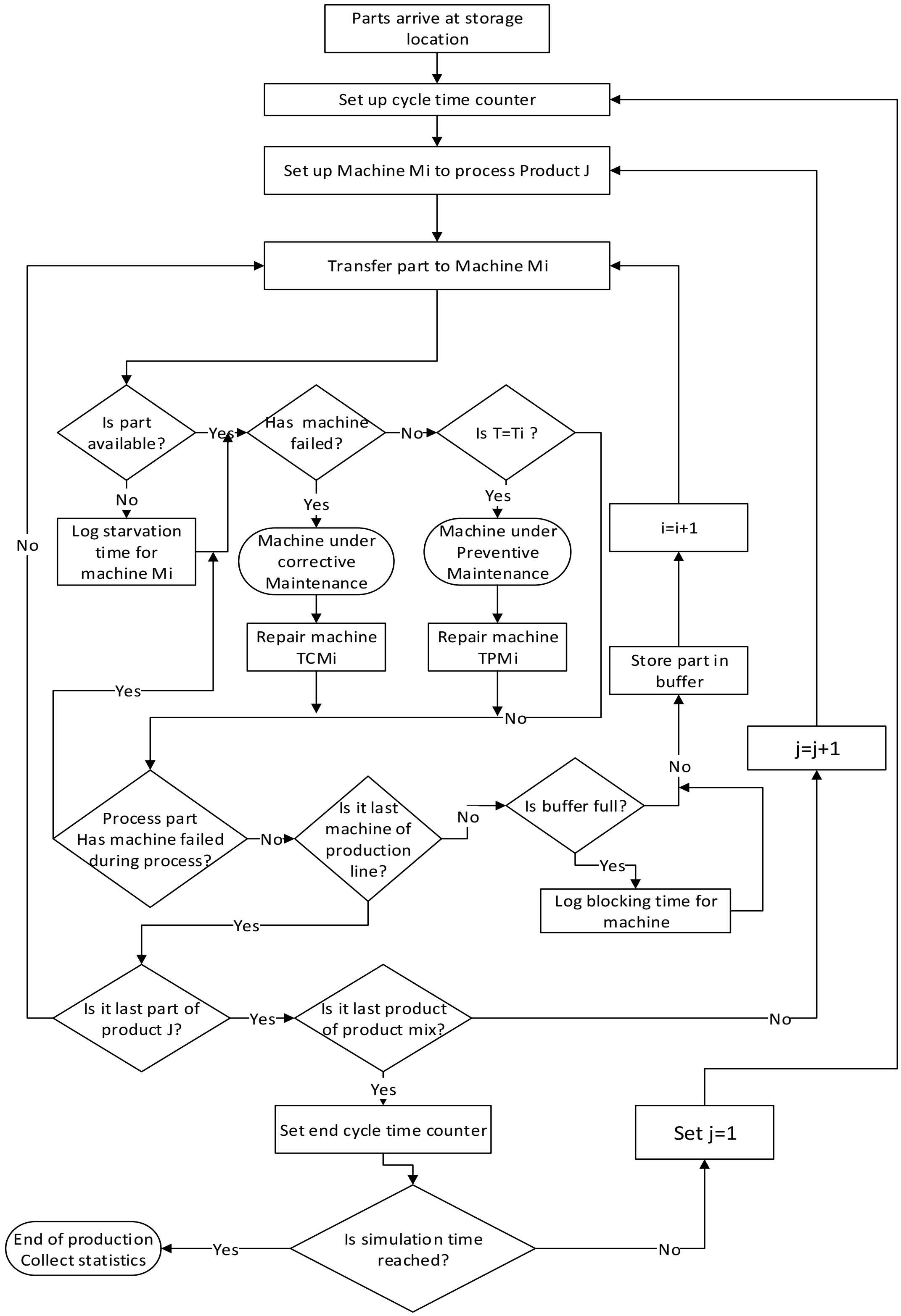

Figure 5: Flow chart of simulation model

Whenever a machine fails during simulation, a resource will go and repair the machine. Preventive maintenance is scheduled during the simulation. Thus, whenever the production line has a PM action, a resource will come and repair the machine. In addition, it will log the scheduled downtime for the machine. However, if the machine is not available, then the part will wait and the program will start to log the blocking time. The part will be processed on the machines as soon as it becomes available. Once the part will finish the process on the machine M_i, the part is transferred to the buffer if it is available. If the buffer is not available, the part will wait on the machine until the buffer becomes available. At the same time, it will start to log the blocking time for the machine. The part will be placed in the buffer as space becomes available.

A part will be moved out of the buffer according to the first-in-first-out (FIFO) rule and will progress to the next machine of the serial production line. Once a part finishes processing through all the machines of the serial production line, it will leave the remanufacturing line and will be placed in the inventory. If it is the last part of product j then program will determine whether each of the products in the product mix are processed. If all the products are not processed, then it will send the next product batch to the machine and the machine will undergo the setup to process the next product j + 1. The setup downtime is used to do the initial preparation for processing the new product. If it is the last part of the product mix, then it will note the cycle time for processing the batches of the product mix.

At this moment, if the simulation time and warm up time is not reached, then it will start the same cycle again and it will transfer the product j again in the same sequence to process. When the runtime of the simulation model is reached, statistics about output results are collected and reported.

4.2 Preventive maintenance calculation:

There are many possible ways to calculate preventive maintenance frequency. All the preventive maintenance strategies that have been used until now are based on failure rates. Some previous research works do not present any relationship between PM and MTBF (Chelbi & Rezg, 2006; Rezg et al., 2005; Zequeira et al., 2008). Generally, preventive maintenance is applied on basis of failure rates. Optimal preventive maintenance time always occurs immediately prior to the average failure rate of the machine.

There is a direct relationship between the preventive maintenance frequency and the MTBF. The MTBF will generally increase as one apply more frequent preventive maintenance. As Meller and Kim (1996) noted, a long run MTBF is a function of the operating time between two preventive maintenance actions and the following three parameters:

1. Current MTBF without the PM action (Min.)
2. Maximum MTBF with frequent PM program (Max.)
3. β - shape factor for the asymptotic gain in PM

Users can calculate the maximum MTBF by choosing a different frequency of PM for any machine. The maximum MTBF can be calculated by the following equation of the machine MTBF, where R is reliability and Y is frequency of PM. Users can get the maximum value of MTBF by choosing a higher frequency of the PM.

$$\text{MTBF} = \frac{\int_0^Y R(T)dt}{1 - R(Y)} \qquad \textbf{(4)}$$

Once user has the maximum value of the MTBF of the machine, user can calculate the shape factor with the following equation.

$$\beta = -R \times \ln\left(1 - \frac{\alpha \max(\text{MTBF}) - \min(\text{MTBF})}{\max(\text{MTBF}) - \min(\text{MTBF})}\right) \qquad \textbf{(5)}$$

In the above equation, R is the rate at which PM is performed to gain the α-percent benefits of the PM. In addition, the shape factor represents the deterioration level of the machine. If the machine has a smaller shape factor, then the reliability of that machine will decrease quickly compared to one that has higher shape factor (Ebeling, 2004). It can be also calculated by plotting the graph between MTBF and shape factor from Equation 6. User must select the most appropriate point on the curve.

Once user has all the MTBF maximum and minimum values along with the shape factor then user can calculate the level of MTBF that can be achieved by applying the preventive maintenance at the different intervals.

$$\text{MTBF} = \text{Min(MTBF)} + (\text{Max(MTBF)} - \text{Min(MTBF)})\,(1 - e^{-\beta/T_i}) \qquad \textbf{(6)}$$

By substituting the different frequencies in Equation 6, one can estimate the achievable MTBF for each machine. Thus, before applying the preventive maintenance to any machine, the values of MTBF can be obtained for different maintenance strategies. This will help to define the best preventive maintenance policy.

4.3 Cost parameters and calculation:

The second objective of this research is to maximize the profit. To find the configuration that will fall in the lowest cost region, one must calculate all the variable costs and overall profit for the firm.

1. To evaluate the overall variable cost, first one need to calculate the maintenance cost related to the system. Users should consider both preventive and corrective maintenance costs to find the overall maintenance cost for the system.

$$\text{Maintenance cost} = C_R \sum TCM_i + C_P \sum TPM_i \qquad \textbf{(7)}$$

2. The second type of variable cost is associated with the buffer: the operating cost of the buffer. All the inventories that have been stored in the buffer, incur some storage cost. While studying the different buffer capacity designs, the cost associated with it also changes because of changes in capacity and its usage. The cost of buffer is calculated by following equation:

$$\text{Buffer cost} = C_B \times BC_i \times T \qquad \textbf{(8)}$$

3. To generate the profit for the firm, one should calculate the total fixed cost for the facility. This cost includes the labor, utility, equipment and building costs.

$$\text{Handling and utility cost} = (C_u + C_h) \times \text{Number of working days} \quad \textbf{(9)}$$

$$\text{Fixed cost} = \text{Handling and utility cost} + C_e + (C_w \times \text{Number of workers} \times \text{Number of working hours}) \quad \textbf{(10)}$$

4. Total cost is the sum of the cost of maintenance, buffer-operating cost and fixed cost of the firm. The following equation calculates the total cost of the firm:

$$TC = \text{Maintenance cost} + \text{buffer cost} + \text{fixed cost} \quad \textbf{(11)}$$

5. The total profit for the remanufacturer is the difference between the revenue and total cost of operating the production line.

$$\text{Profit} = (\text{Finished Products} \times \text{selling price}) - TC \quad \textbf{(12)}$$

4.4 Experimental design:

In a multiproduct production line, there are number of factors (independents variables) that can affect the cycle time and cost of the system. As the number of factors increases in the production line, the number of experiments increases as well. Thus, for longer production lines, more experiments are needed to assess the performance of the production system. Therefore, a mixed level fractional factorial design has been designed to estimate the effect of major factors on the performance of the production line. The analysis of variance (ANOVA) will be applied on results to identify the most contributing factors to the performance of the remanufacturing line. The best results will be optimized further by using the Sim Runner optimizer, which is available in the software package PROMODEL (2016). The solution approach is shown in Figure 6.

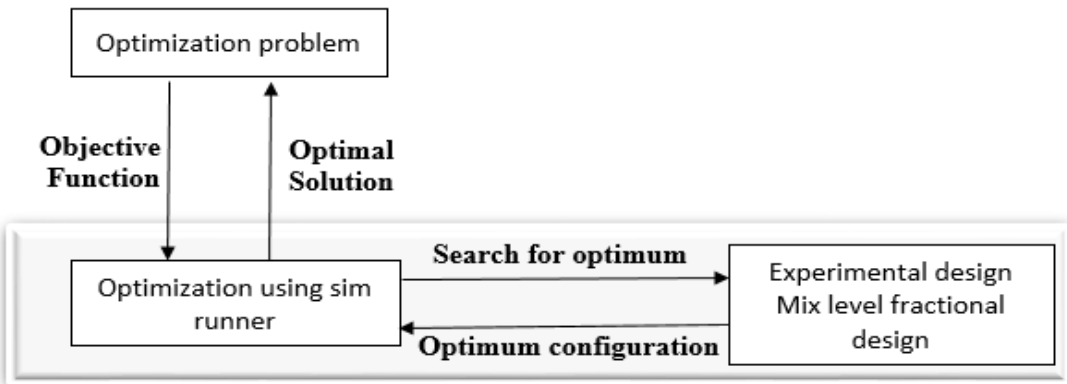

Figure 6: Solution approach

By using this solution approach, the configuration any remanufacturing line can be optimized. To optimize the remanufacturing line, experimental design is generated and taken as an input in the simulation model. The simulation model will work as shown in Figure 5 and results will be analyzed using Minitab. The optimum scenario from the experimental design will be identified and taken as an input in Sim Runner for further optimization. Sim Runner will optimize the remanufacturing line parameters. Sim Runner is a built-in optimization software in the PROMODEL package, which helps to optimize the goals within the given boundary conditions by using an evolutionary algorithm. The proposed solution approach has been applied in case studies to show the effectiveness of this approach. The details about ProModel is given in Appendix C and details about Sim Runner is given in Appendix D. Chapter 5 shows the use of the simulation-based experimental methodology in different remanufacturing lines.

Chapter – 5: Case study

This chapter of the thesis represents the application of the proposed methodology on real world remanufacturing companies. In this section, the simulation based experimental methodology is applied on five-machine four-buffer and nine-machine eight-buffer production lines. Analysis of variance (ANOVA) is applied on the simulation results to understand the impact of the different variables on the production line.

5.1 Introduction:

Electronic items like cell phones, computers, laptops, and tablets have become an important part of our life. Since the introduction of these electronic items, different models have increased the competition in the market. In today's world, these devices are necessary to make our day-to-day life comfortable. Every year, millions of new devices are sold in the market and on the other hand, millions of electronic devices are returned to the manufacturers. However, very few devices are remanufactured each year and the remaining are disposed in the landfill. Therefore, the consumption of untapped resources is continuously increasing day by day. By recycling and remanufacturing these devices, we can generate the huge revenue and it will decrease the consumption of untapped resources. The average life of different electronic devices in USA and Canada is depicted in Table 2.

Table 2: Average life of different products

Product	USA	Reference	Canada	Reference
Cell phone	17.5 months	Kim & Paulos, 2011	22 months	CWTA,2013b
Computer	3 to 4 year	Yang & Williams, 2009	3 to 4 years	Yang & Williams, 2009
Computer (work)	2 to 3 year	Yang & Williams, 2009	2 to 3 year	Yang & Williams, 2009
Laptop	2 to 3 year	Yang & Williams, 2009	2 to 3 year	Yang & Williams, 2009

As one can see in Table 2, some electronic products have very short life cycle. Even the return rate of products is high in the market. Only a nominal percentage of products are remanufactured. Table 3 shows the returned and remanufactured quantity for different products in the USA.

Table 3: Sold and returned quantity of different products

Product	Selling quantity/ quantity in market	Reference	Returned quantity	Reference
Cell phone	250 million users	Asheeta et al., (2008)	130 million	Osibanjo & Nnorom, (2008)
Computer	60 million / year	Ravi et al., (2005)	12 million return & 10% are remanufactured	Ravi et al., (2005)
Laptop	16.4 million /year	Yang & Williams, (2009)	15.75 million	Yang & Williams, (2009)

The capacity of the remanufacturing facilities to explore the opportunity of remanufacturing need to increase, because only 10% to 20% of returned products pass through the remanufacturing process. A case study for a computer remanufacturing company is presented to explore the performance improvement opportunities in the remanufacturing industry.

5.2 Five machine and four-buffer production line:

A case study is performed on five-machine and four-buffer production line, which is used to remanufacture the computer and laptops. A simulation model is created using the commercial software package PROMODEL 2016. The returned computers and laptops must pass through certain operations to get new life. The detailed remanufacturing processes are shown in Figure 7. Products arrive to the facility at every 4-hour interval and the retuned quantity for computers and laptops is depicted in Table 4. These returned products will pass through the inspection and testing. At the inspection station, some basic memory and cache tests will be done on the product and good quality products will proceed to the labelling station, and remaining products will go to testing. Products with bad quality will go to the material recovery operations after finishing the testing operation. After the testing operation, moderate quality products will go to the remanufacturing stage. In the case study, it is assumed that batches will have 10% good quality products, which will proceed to labelling stations after inspection. On other hand, 10% products will be found unrepairable after the testing operation and these products will proceed to the material recovery. The processing time for each stage is shown in the Table 5.

Table 4: Batch size of the products

Computer	200
Laptop	160

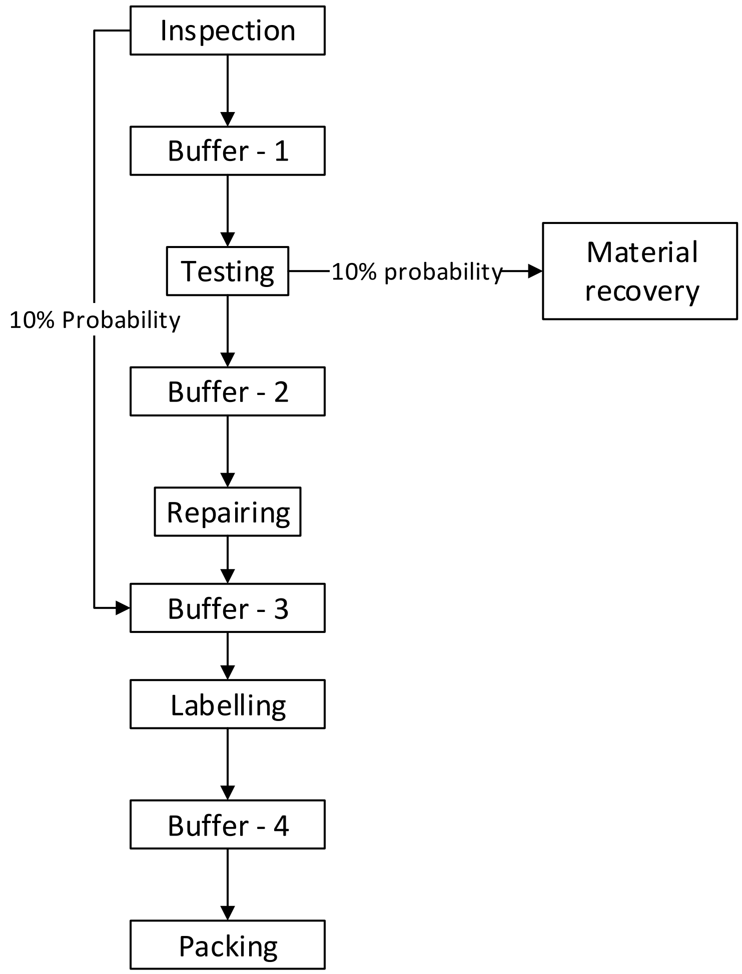

Figure 7: Computer and laptop remanufacturing line operations

The processing times are exponentially distributed in the simulation model, since the exponential distribution can introduce the large set of possible values for the processing times. One cannot assume the deterministic time for the returned products, as the processing times are dependent on the quality of the returned products. Thus, the exponential distribution is the best choice to explore the randomness of the processing time for returned products. The processing times are taken from Li et al., 2009.

Table 5: Processing times of computer and laptop remanufacturing

Taken from Li et al., 2009.

Type of Operation	Computer (min)	Laptop (min)
Setup time	30	30
Inspection	e (1.23)	e (1.05)
Testing	e (7.32)	e (6.5)
Repairing	e (20)	e (15)
Labelling	e (5.66)	e (5.66)
Packing	e (9.1462)	e (9.1462)
Material recovery	e (5.725)	e (5.025)

All machines are treated as unreliable and semi-automated and are subject to random failure and repair rates. The failure and repair rates are exponentially distributed. Failure and repair rates for each machine are shown in Table 6.

Table 6: Failure and repair rates for remanufacturing line

Work station	Failure rate (hrs.) (λ)	Repair rate (hrs.) (μ)
Inspection	1	10
Testing	1.33	12
Remanufacture	0.86	7.5
Labelling	0.75	6
Packing	1	8.6

As one can see in Table 5, the remanufacturing stage has higher service time. Hence, two remanufacturing machines are used in the production line and for all other machines, the quantity is one. The material recovery machine is a reliable machine. It does not experience any failure during the process. The collection, labor, utility & handling, selling, and equipment costs are taken from Li et al., (2009). The holding, utility, and other fixed costs are given in Table 7. The selling price of remanufactured products is depicted in Table 7.

Table 7: Cost associated with the computer remanufacturing

Category of cost	**Cost**
Worker	$15 per hour
Utility and holding cost	$93 per day
Collection cost of computer	$150 per computer
Collection cost of laptop	$200 per laptop
Equipment cost	$811000 per year
Corrective maintenance cost	$100 per hour
Preventive maintenance cost	$10 per hour
Space cost	$0.2774 per sq. feet / hour
Selling price of computer	$250 per computer
Selling price of laptop	$400 per laptop

The computers and laptops with bad quality are sent for material recovery. By recycling a computer, different materials can be recovered. The recovery of the materials can be profitable for the firm. The value and the percentage of the recoverable materials in the computer are illustrated in Table 8.

Table 8: Recoverable materials in computer (Bhuie et al., 2004)

Material	Percent	Value ($)
Plastics	23.00	11.73
Aluminum	6.30	9.11
Steel	20.50	4.18
Gold	0.001	6.27
Silver	0.02	1.03
Lead	6.30	1.93
Cadmium	0.01	0.01
Mercury	0.0022	0.00
Total	**56.13**	**$34.26**

5.3 Preventive maintenance frequency calculation:

The failure and repair rates for each machine are indicated in Table 6. To calculate the preventive maintenance frequency, we must follow the methodology defined in Section 4.2. First, one need to decide the maximum MTBF of the machine, which one can achieve by the frequent preventive maintenance. By substituting the frequency of preventive maintenance in Equation 4, the maximum MTBF is calculated. Each machine can achieve the availability of 99% with the maximum value of the MTBF. 15 and 35 minutes' frequencies are selected to apply the PM. The graph between shape factor and different frequencies is plotted by using Equation 6 and appropriate shape factor is estimated from the graph. The estimated value of the shape factor (β) is shown in Table 9.

Table 9: Maximum MTBF (hrs.) and shape factor (β)

	Inspection	Testing	Remanufacture	Labelling	Packing
MIN.	1	1.33	0.86	0.75	1
MAX.	10	8.33	15	11.66	13.33
β	7.5	12.5	27	27	6

The parameters of Table 9 are used to find the achievable MTBF for different preventive maintenance frequencies. Equation 6 calculates the achievable MTBFs for the chosen frequencies and achievable MTBFs for these two frequencies are displayed in Table 10. The MTBF calculation for the inspection machine is given below and remaining MTBFs are calculated by using a similar method:

$$MTBF = Min\ (MTBF) + (Max\ (MTBF) - Min\ (MTBF))\ (1 - e^{-\beta/Ti})$$

$$MTBF = 1 + (10 - 1)\ (1 - e^{-7.5/15}) = 4.54 \text{ hours}$$

In the real world, it is very hard to apply the preventive maintenance at the same interval. There is always some variation in the defined frequency. The normal distribution is used in the simulation model to apply the effect of variation in the preventive maintenance interval. Table 10 shows the distribution used in the simulation model.

Table 10: Preventive maintenance frequency and MTBF (hrs.)

Frequency	Inspection	Testing	Remanufacture	Labelling	Packing
N (15, 5) min	4.54	5.3	13	10	5.9
N (35, 5) min	2.7	3.4	8.4	6.5	2.9

5.4 Warm up period calculation:

In the simulation, a warm up period is necessary to remove the initial bias from the system. If users do not apply the warm up period, then the collected results have some errors, as they are not taken when the system is in a stable state. By adding the warm-up period, user can collect the data when the system is statistically stable. The warm up period does not represent a real remanufacturing system and results do not include the data collected in the warm up period. The warm-up period can be determined by two methods. The first method is Welch's moving average method and second method is the batch means method. Here, Welch's moving average method is used to find the warm up period.

$$\bar{Y}_i(w) = \begin{cases} \dfrac{\sum_{s=-(i-1)}^{i-1} \bar{Y}_{i+s}}{2i-1}, \text{ if } i = 1, \ldots, w \\[2ex] \dfrac{\sum_{s=-w}^{w} \bar{Y}_{i+s}}{2w+1}, \text{ if } i = w+1, \ldots, m\text{-}w \end{cases} \quad \textbf{(13)}$$

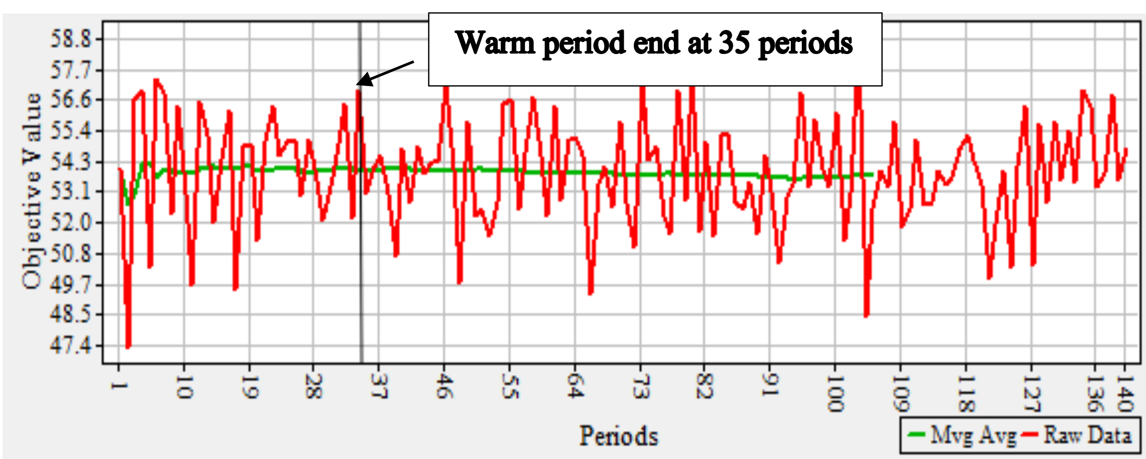

Figure 8: Warm up period graph

Welch's moving average can be calculated by Equation 13. The five machine and four buffer production line model was run for 2800 hours. The logic behind simulating the model for 2800 hours is that industry has 8 hours shift a day and 350 working days in a year. Thus, a simulation of 2800 hours will calculate the results of the firm for one year. The total simulation time is divided into 140 intervals. The simulation results are recorded at 20-hour intervals. We calculated the moving average for the different windows and graph showed stabilization for w = 35. Therefore, the warm-up period was selected to be 35 periods of 20 hr. each for a total of 700 hr. Figure 8 represents the graph of Welch's moving average method, which is helpful to determine the warm up period. The warm up period ends after 35 periods and one can see that the graph is stable after the warm up period.

5.5 Mix level fractional factorial design:

Experimental designs are best to understand the effect of each variable on the production line. Generally, full factorial design is used to analyze the experiment. However, when one have more than two levels and the number of factors is more than four, then the number of experiments increases above 500. It is very hard to perform such a considerable number of experiments and analyze the results. To analyze this type of design, one have to use the fractional experimental design, which assists in optimizing the experiment size. In fractional design, only the main effect and the two-way effect of each factor are included, which helps to analyze the experiment in the same way as user can do with the full factorial design. After the brief literature review, the following factors are determined, which can make a noticeable impact on the production output and cost of the system.

a) Buffer-1 capacity

b) Buffer-2 capacity

c) Buffer-3 capacity

d) Buffer-4 capacity

e) PM frequency

f) PM duration

The levels of each factor are chosen by conducting the experiments. From the experiments, the cycle time has a maximum value when all buffers have a capacity of 5 and the minimum cycle time was noticed when all buffers are kept at 20. The medium level was determined by performing more experiments at intermediate buffer values. When all the buffers have a capacity of 10, then the achievable cycle time was moderate. PM frequencies are defined in Table 10. The lowest level for preventive maintenance frequency was N (15,5) minutes as one can reach the maximum MTBF with this frequency. N (35,5) minutes frequency was chosen as the higher level for the preventive maintenance. Intermediate level will have mixed preventive maintenance frequency. A machine with the higher failure rate will get maintenance that is more frequent and the remaining machine will get less frequent maintenance. In this case study, inspection and packing machines have a higher failure rate. Therefore, these two machines will get maintenance at N (15,5) minutes interval and remaining machines will go under maintenance at N (35,5) minutes interval in intermediate level preventive maintenance. Table 11 shows all the factors with their levels.

Table 11: High and low level for factors of computer remanufacturing line

Factor	Low	Medium	High
Buffer 1 (A)	5	10	20
Buffer 2 (B)	5	10	20
Buffer 3 (C)	5	10	20
Buffer 4 (D)	5	10	20
PM Freq. (E)	15	25	35
PM Duration(F)	1		2

By entering the data of Table 11 in the JMP-13 statistical software, a fractional design was modeled. As a result, list of 66 different scenarios is generated to analyze the production line. These 66 scenarios were taken as an input in the PROMODEL. From the results, cycle time and cost are achieved as the response variable to analyze the performance of the system. The experiment is replicated 10 times to produce the accurate results. The calculation of the number of replications is shown in Appendix 2. Table 12 presents the fractional design and average results of the simulation model for 10 replications.

Table 12: Results of computer remanufacturing line

No	A	B	C	D	E	F	CT (hrs.)	Profit ($)
1	10	10	10	20	15	1	57.83	224470.53
2	20	5	10	5	25	1	60.91	157765.86
3	10	10	20	5	15	1	58.91	192666.03
4	20	10	10	10	15	1	60.32	155671.67
5	10	20	20	5	15	2	63.94	44228.24
6	20	5	20	5	25	2	62.58	88636.25
7	20	5	10	5	15	2	63.59	61140.38

8	20	5	5	10	25	2	62.82	93434.24
9	10	20	10	5	15	1	62.42	109525.48
10	5	10	10	20	35	2	57.95	217968.19
11	10	5	10	5	25	2	61.46	137489.68
12	5	10	20	5	35	2	59.38	177279.62
13	10	20	20	20	15	1	59.96	155825.76
14	20	10	5	10	35	2	62.85	82636.44
15	20	20	10	20	35	1	62.66	81683.20
16	**5**	**5**	**5**	**20**	**25**	**1**	**56.53**	**288117.43**
17	20	10	20	10	25	1	59.97	152989.16
18	10	20	5	10	35	2	62.70	82244.29
19	5	10	20	10	15	1	57.14	258307.29
20	10	20	5	5	25	2	65.52	26801.19
21	5	20	10	20	25	1	59.49	180313.27
22	5	10	5	20	15	1	57.52	249179.61
23	10	10	20	20	25	2	60.61	134414.15
24	20	5	10	20	25	2	62.13	110632.49
25	20	10	10	5	25	2	64.16	43979.18
26	5	5	5	10	35	2	58.63	214779.75
27	20	20	20	10	15	2	65.29	11307.82
28	5	20	20	20	35	2	60.59	130751.58
29	5	20	5	10	25	1	60.57	161945.72
30	10	10	5	5	35	2	62.47	112243.63
31	10	5	5	20	15	2	60.35	156253.25
32	20	5	10	10	35	2	61.31	134842.01
33	5	5	5	5	15	2	61.87	136982.39
34	10	20	10	10	25	2	63.59	69796.12
35	20	20	20	5	15	1	63.59	64006.73
36	10	20	10	20	35	2	62.16	99331.44
37	10	5	5	5	35	1	59.94	177767.66

38	5	5	10	10	15	1	57.15	265646.58
39	5	20	5	10	15	2	62.99	85444.49
40	5	5	20	20	15	2	58.32	199769.98
41	20	20	5	20	25	2	65.75	8284.29
42	20	10	20	20	15	2	62.52	76439.69
43	10	20	20	5	35	1	61.39	127784.78
44	5	10	10	10	25	1	57.51	242439.24
45	20	5	5	20	35	2	60.76	135619.98
46	10	10	5	20	25	1	58.32	220209.39
47	10	10	5	10	15	1	58.80	200426.94
48	20	10	10	5	35	1	61.63	118811.03
49	5	20	20	5	25	1	60.35	154600.84
50	5	20	10	20	15	2	62.35	103190.55
51	20	20	5	5	35	1	65.17	32557.35
52	5	10	10	5	15	2	61.40	139809.47
53	5	20	10	5	35	2	62.01	109556.30
54	10	10	20	10	35	2	58.97	179209.70
55	10	10	20	20	35	1	57.76	214034.64
56	10	5	10	10	15	2	60.74	149337.48
57	10	5	20	10	25	1	56.93	252433.96
58	5	20	10	10	35	1	59.76	171314.13
59	5	5	20	5	35	1	57.27	261683.69
60	10	5	10	20	35	1	57.25	244282.24
61	5	5	20	10	25	2	58.56	199349.35
62	20	5	5	20	15	1	59.44	179656.37
63	20	5	20	10	35	1	58.79	176940.94
64	5	10	5	20	25	2	60.23	157118.88
65	5	10	5	5	25	1	59.58	189316.02
66	5	20	5	20	35	1	59.69	169270.57

5.6 Analysis of variance (ANOVA):

The results of the simulation model were substituted in the MINITAB 2016 statistical software to perform the Analysis of variance (ANOVA). ANOVA and regression analysis of variance was calculated in MINITAB and the results of ANOVA and regression are shown in Table 13.

Table 13: Analysis of variance (ANOVA)

S = 0.674210					
R-Sq = 92.43%					
R-Sq. (adj) = 92.12%					
Source	**DF**	**SS**	**MS**	**F**	**P**
Regression	26	3511.47	135.057	297.12	0.000
Residual Error	633	287.74	0.455		
Total	659	3799.21			

In Table 13, DF represents the degrees of freedom. the number of degrees of freedom is the number of values in the final calculation of a statistic that are free to vary. Term SS represents the sum of squares. SS represents the sum of squared differences from the mean and is an extremely important term in statistics. The P value, or calculated probability, is the probability of finding the observed, or more extreme, results when the null hypothesis (H_0) of a study question is true – the definition of 'extreme' depends on how the hypothesis is being tested. The regression analysis report depicts the R^2 = 92.43%, which indicates the good fit of the data. In addition, F ratio is high and equal to 297.12. This shows the high variation within sample means. The confidence interval value is 95% in the analysis of the results and the p-value is less than 0.05, showing the significance of the test.

Table 14: Coefficients of regression analysis

Term	Coef	SE coef	t	P
Constant	60.2621	0.11689	515.548	0.000
A	1.5988	0.03610	44.290	0.000
B	1.6803	0.03692	45.508	0.000
C	-0.5732	0.03894	-14.721	0.000
D	-0.8095	0.03462	-23.384	0.000
E	-0.3299	0.03639	-9.066	0.000
F	1.1336	0.02908	38.989	0.000
A*A	-0.0671	0.06773	-0.990	0.322
B*B	0.3509	0.07001	5.012	0.000
C*C	0.1926	0.06723	2.865	0.004
D*D	0.8369	0.07024	11.915	0.000
E*E	-0.2911	0.06008	-4.846	0.000
A*B	0.1812	0.04337	4.179	0.000
A*C	0.0106	0.04592	0.230	0.818
A*D	0.0259	0.04170	0.621	0.535
A*E	0.0542	0.04461	1.215	0.225
A*F	0.0796	0.03635	2.190	0.029
B*C	0.0138	0.04446	0.311	0.756
B*D	0.0752	0.04059	1.852	0.064
B*E	-0.0019	0.04277	-0.043	0.965
B*F	-0.0215	0.03420	-0.630	0.529
C*D	0.2494	0.04299	5.803	0.000
C*E	0.0547	0.04507	1.214	0.225
C*F	-0.0265	0.03500	-0.757	0.449
D*E	-0.0026	0.03957	-0.065	0.948
D*F	0.0527	0.03311	1.592	0.112
E*F	-0.3186	0.03689	-8.638	0.000

Table 14 shows the different coefficients of the regression analysis. The analysis indicates that buffer 3(C), buffer 4 (D) and preventive maintenance frequency (E) have a positive impact on the cycle time. We can see that the buffer 4 (D) has the largest impact on the cycle time and its value is -23.384, which means buffer 4 is significant to reduce the cycle time. Buffer 4 is followed by buffer 3 and preventive maintenance frequency with t = -14.721and t = -9.066 respectively. The negative t-value denotes the reduction in the cycle time due to those factors. Buffer 1 (A) and buffer 2 (B) negatively affect the cycle time of the system as they have the largest positive value of the t-statistics. The value of the p-statistics is lower than the confidence interval. Therefore, one can conclude that all the factors are significant in the experiment. From the regression analysis, one can say that buffer 2 and buffer 1 should have lower capacity, while buffer 3, buffer 4 and preventive maintenance frequency should have higher values. As per the results of the cycle time and cost, the best scenario is scenario number 16 with the lowest variation in cycle time and cost for both replications. Scenario 16 is then optimized by using Sim Runner and the optimized results are given in Table 15.

Table 15: Optimized results for computer remanufacturing line

Scenario no	**A**	**B**	**C**	**D**	**E**	**F**	**CT (hrs.)**	**Profit ($)**
16	1	4	5	20	25	1	55.19	316,948

As one can see in Table 15, further optimization of the experimental design results has lowered the average cycle time. Profit of the firm has also increased with the reduction in the buffer size. Therefore, experimental design can be useful to achieve the best preventive maintenance strategy and optimal buffer allocation.

5.7 Revenue generated by recycling products:

In the model, the best scenario is 16 and it generates the maximum output for the system. Therefore, the Recycled quantity of computers is selected from scenario 16 to calculate the revenue. Once computers are recycled, valuable materials such as gold, silver, and platinum can be recovered. The metal present in a regular computer is given in Table 8. By recycling a computer or laptop, one can generate the average revenue of $34.46. Table 16 shows the recycled quantity of each product and total revenue for the firm.

Table 16: Revenue generated by recycling computers and laptops

	Computer(units)	Laptop (units)	Revenue ($)
Average	886	691	54343.42

One can generate an average $54000 revenue by processing the 17,640 used products. Therefore, instead of throwing the electronic products, it should be used to recover the material, as it can be profitable for a company. Even the natural resources can be preserved and pollution and energy consumption can be reduced by recycling the products.

5.8 Extension to longer production line:

Analysis of variance denoted that the buffer capacities and frequency of the preventive maintenance could be a vital factor to achieve higher production rate in the remanufacturing line. Therefore, one can say that the optimal combination of the buffer allocation and preventive maintenance frequency is beneficial to increase the output of the production line. It also decreases the variable cost associated with the production line. In this section, the suggested methodology has been applied to a longer production line to assess its effectiveness in such as setting of longer production line.

5.8.1 Nine machine-eight buffer production line:

A nine machine-eight buffer production is studied in this section that remanufactures the cell phones and tablets. Cell phones and tablets must pass through the operation like inspection, disassembly, repair, polishing, and software update. The detailed remanufacturing process for this case study is shown in Figure 9.

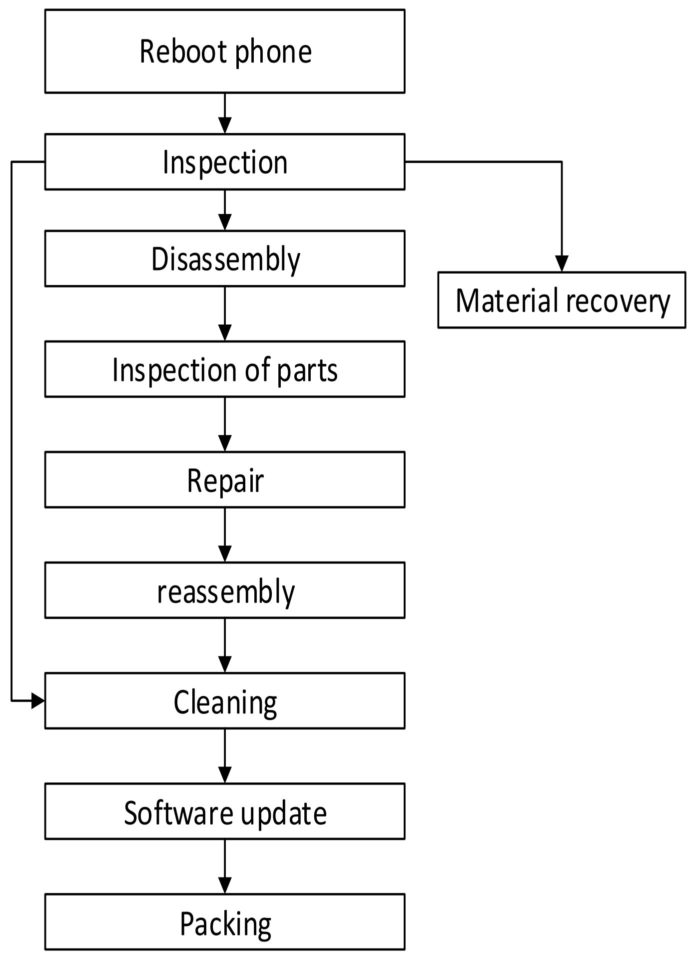

Figure 9: Cell phone and tablet remanufacturing line operations

The returned products will go under the phone reset station and the product will be reset to default. All the returned products will pass through inspection. Products with good quality will directly proceed to the polishing and cleaning operation, while bad quality products will be sent to material recovery. It is assumed that 15% of the products will have good quality and 15% of the products will have bad quality. The remaining 70% of the products (moderate) will go through the sequence in the remanufacturing line. It is assumed that the operations like rebooting, cleaning and reassembly will not need any machine. Thus, these operations are reliable operations. Other operations are supported by the machines and all the machines are semi-automated. The processing time for each product is given in Table 17. The cell phone processing times are adapted from Kang et al., (2001). The failure and repair rates are adapted from Noseworthy & Abdul-Kader, (2004).

Table 17: Processing times for cell phone remanufacturing process Adapted from Kang et al., 2001.

Work station	Cell phone (min)	Tablet (min)
Reboot	E (1.5)	E (1.5)
Inspection	E (1.5)	E (2)
Disassembly	E (1)	E (2.5)
Inspection of parts	E (3)	E (3)
Repair	U (9,15)	U (10,18)
Reassembly	E (3)	E (4)
Cleaning	E (4)	E (4)
Updating of phone	E (3.5)	E (4.5)
Packing	E (1.5)	E (1.5)

Machines will undergo the setup to process the next products, as the production of the last product is completed. The setup time for each machine is 10 minutes. Products are processed in batches. The batch size of cell phones is 80 and the batch size of tablets is 50. The failure rates for unreliable machines are illustrated in Table 18.

Table 18: Failure and repair rates for cell phone remanufacturing line

Work station	**Failure rate (λ)**	**Repair rate (μ)**
Disassembly	1	10
Inspection of parts	1.33	12
Repair	0.86	7.5
Updating	0.75	6
Packing	1	8.6

The collection and remanufacturing costs are displayed in Table 19. The selling price of each product is also shown in Table 19. Cell phone buy back and remanufacturing costs are taken from Pandian & Rajan (2015). The remanufacturing cost includes the fixed cost related to the firm. The cost of maintenance and buffer will be obtained from simulation results and then added to the total cost to calculate the profit.

Table 19: Collection and selling price of cell phone and tablets

Cost category	**Cell phone**	**Tablet**
Buy back price	$54.33	$90
Remanufacturing cost	$120.67	$130
Average selling price	$200	$250

The bad quality cell phones are sent to material recovery. Different cell phones have different materials in diverse proportions. Therefore, the average value of the material in a cell phone is calculated and used to find the revenue from material recovery. Table 20 shows the average proportion of various material in a cell phone as well as the value of the materials. One can recover $1.45 by recycling each cell phone on average.

Table 20: Recoverable material in cell phones

Geyer & Blass, (2010).

Material	Average proportion in grams	Price of the material (cents)
Silver	0.505	18.22
Aluminum	4.36	1.175
Gold	0.0295	63.13
Chromium	0.46	0.375
Copper	14.99	10.21
Iron	4.66	0.465
Nickel	1.72	4.17
Lead	0.54	0.095
Palladium	0.045	46.685
Tin	0.615	0.565
Zinc	0.595	0.21
Total	**28.5195**	**145.3**

5.8.2 Mixed level fractional factorial design:

The cell phone remanufacturing line has nine machines and eight buffers. All eight buffers have some impact on the production line. To understand the impact of each buffer, the fractional design is modeled by using the capacity of each buffer as a factor. Thus, total nine factors for the production line has been selected. Because of the large experiment size, the design is reduced to two-level fractional design. The preventive maintenance frequency has three levels as defined in the first case study. Table 21 presents the factors and their levels for the fractional factorial design. For the medium level of preventive maintenance, the disassembly and packing machines have more frequent maintenance and the remaining machines have less frequent maintenance.

Table 21: High and low level for cell phone remanufacturing line

Variable	Low level	Medium level	High level
Buffer 1 (B1)	1		20
Buffer 2 (B2)	1		20
Buffer 3 (B3)	1		20
Buffer 4 (B4)	1		20
Buffer 5 (B5)	1		20
Buffer 6 (B6)	1		20
Buffer 7 (B7)	1		20
Buffer 8 (B8)	1		20
PM TIME (PM)	15	25	35

By using the parameters in Table 21, a fractional design is created in JMP-13 statistical software. This design has 60 different scenarios to analyze the production line. All 60 experiments were simulated for a 3500-hour run period including a 700-hour warm up period was added at the beginning of the simulation to note the results in steady state. Results are recorded for four replications. The results and the fractional design are given in Table 22. Later, an analysis of variance is performed on the results; it is shown in Table 23.

Table 22: Results of nine-machine production line

no	b1	b2	b3	b4	b5	b6	b7	b8	PM	CT(hrs.)	Profit ($)
1	20	1	20	20	1	1	1	1	25	20.53	165071.15
2	1	20	20	1	1	20	1	1	25	19.69	165070.82
3	1	1	1	1	1	20	1	1	15	12.14	344591.83
4	1	1	20	20	1	1	1	20	25	19.79	186121.52
5	1	1	20	1	20	20	20	1	15	17.23	191151.98
6	20	20	1	20	1	20	20	1	15	17.27	174730.08
7	1	1	1	20	20	20	20	20	15	15.64	213857.38
8	20	1	1	20	1	1	20	20	35	15.08	254442.24
9	20	1	20	1	20	20	20	20	25	15.09	216065.17
10	20	20	20	1	1	1	20	1	35	16.96	201451.73
11	20	1	1	20	20	1	20	20	25	15.95	214780.92
12	20	1	1	20	20	1	1	1	15	20.45	162352.35
13	20	20	20	1	20	1	1	20	25	17.65	185251.27
14	20	1	1	20	20	20	1	1	35	19.84	152699.52
15	1	1	20	1	1	1	20	1	25	15.39	254634.81
16	1	1	20	20	1	1	20	1	15	17.29	205536.54
17	1	20	20	20	20	20	20	20	35	11.99	285934.96
18	1	20	20	20	20	1	20	1	25	11.69	303507.34

19	20	20	20	20	20	1	20	20	15	11.69	293766.87
20	20	20	20	20	1	20	20	20	25	12.95	252031.32
21	1	1	20	1	1	1	1	1	35	18.31	214700.62
22	20	1	20	1	20	20	1	1	15	20.01	146763.98
23	1	20	1	1	1	20	20	1	35	14.47	254272.28
24	1	20	1	20	1	1	1	1	25	20.42	174577.96
25	1	20	1	1	1	1	1	20	35	17.71	223395.30
26	1	20	20	20	20	20	1	1	15	13.19	255653.77
27	1	1	1	20	20	1	20	1	35	17.04	210837.42
28	1	1	20	1	20	20	1	20	35	18.94	180587.69
29	20	20	1	1	1	1	20	20	25	15.15	246535.73
30	20	20	20	20	1	20	1	20	35	16.43	186796.01
31	20	20	1	20	20	20	1	20	25	16.73	179193.77
32	1	1	1	1	20	1	1	1	25	17.72	225871.91
33	20	20	1	1	20	20	1	20	15	19.16	160229.05
34	20	1	20	20	1	20	1	20	15	19.05	163665.67
35	20	1	1	1	20	1	1	20	35	17.07	219905.94
36	20	20	20	1	1	1	1	1	15	20.87	151712.44
37	20	20	1	1	1	20	1	1	35	17.40	200862.36
38	1	1	20	1	20	1	1	20	15	19.69	183030.64
39	20	1	20	20	20	1	1	20	35	17.54	183703.37
40	20	20	1	20	1	1	1	20	15	19.83	166446.00
41	20	20	20	1	20	20	20	20	35	13.54	241445.73
42	20	20	1	1	20	20	20	1	25	16.78	180110.64
43	1	20	20	1	1	20	20	20	15	15.13	228671.21
44	1	1	1	20	1	20	1	20	35	16.61	228236.57
45	20	1	20	1	20	1	20	1	35	17.02	196059.91
46	1	20	20	20	1	1	20	20	35	15.07	239800.36
47	20	1	1	1	1	1	20	1	15	12.10	339337.45
48	1	20	1	1	20	1	20	1	15	17.30	203315.62

49	1	1	1	20	1	20	20	1	25	14.46	256318.88
50	1	20	20	1	20	1	1	1	35	18.16	185514.08
51	1	20	1	20	20	1	1	20	35	17.62	196129.43
52	1	1	20	1	20	1	20	20	35	16.08	232044.19
53	20	1	1	1	1	20	1	20	35	11.96	337106.02
54	**20**	**1**	**1**	**1**	**1**	**20**	**20**	**20**	**25**	**11.83**	**341456.23**
55	1	1	20	20	20	20	1	1	25	17.58	186843.12
56	1	1	1	1	1	1	20	20	15	12.11	351674.01
57	1	20	1	1	20	20	20	20	25	15.06	234187.82
58	20	20	1	20	20	1	20	1	35	15.10	215718.60
59	20	1	20	1	1	1	20	20	15	15.20	246892.12
60	20	1	20	20	1	20	20	1	35	16.65	186472.76

Table 23: Analysis of variance for nine-machine line

S = 0.496738					
R-Sq = 96.99%					
R-Sq. (adj) = 96.28%					
Source	**DF**	**SS**	**MS**	**F**	**P**
Regression	46	1535.78	33.387	135.31	0.000
Residual Error	193	47.62	0.247		
Total	239	1583.40			

The F ratio is high and equal to 96.99%, which shows the high variation within the means of the sample. The R-square value is very high, indicating a good fit of the data. The p-value is close to zero. Thus, the model is significant. To find the contribution of each factor, a regression analysis was performed on the data. Results of the regression analysis are given in Table 24. From the Table 24, one can say that buffer 6, buffer 7, and buffer 8 have a significant impact on the cycle time of the production line. These three buffers should have a higher capacity to achieve the lowest cycle time. From Table 24, one can say the buffers are highly responsible for the optimization of the cycle time. However, preventive maintenance does show a significant impact on cycle time as well.

Table 24: Regression analysis for nine-machine line

Term	Coef.	SE coef.	t	P
Constant	16.2374	0.06905	235.166	0.000
b1	0.0688	0.03621	1.900	0.009
b2	-0.0269	0.03465	-0.777	0.438
b3	0.0894	0.03530	2.533	0.012
b4	0.0739	0.03503	2.109	0.036
b5	0.0329	0.03539	0.931	0.353
b6	-0.4288	0.03492	-12.279	0.000
b7	-1.3186	0.03499	-37.681	0.000
b8	-0.3919	0.03666	-10.691	0.000
PM	-0.1751	0.04421	-3.960	0.000

From Table 23, the lowest cycle time and the maximum profit was generated in scenario 54. In this scenario, buffer-6, buffer-7, and buffer-8 are kept at the higher level of 20. From the regression analysis, one can conclude that these three buffers should have higher capacities. Thus, user can easily determine the best configuration of the production line by ANOVA and regression analysis. From the experimental design, one can notice the best buffer allocation in scenario 54. The Sim Runner software optimized this scenario and the optimal results are shown in Table 25, and the corresponding revenue generated from the recovery of material is computed, see column under Recycle profit.

Table 25: Optimal results for the nine-machine remanufacturing line

Scenario No	B1	B2	B3	B4	B5	B6	B7	B8	Pm	CT(hr.)	Profit ($)	Recycle profit ($)
54	1	1	1	1	1	2	10	12	25	11.56	372345	6743

After studying the longer production line, one can conclude that simulation based experimental methodology can be applied in any remanufacturing line to optimize the parameters like buffer capacity and preventive maintenance frequency. Simulation based experimental methodology decreases the number of experiments needed to optimize the configuration of the production system. An analysis of experimental design by using ANOVA and regression analysis is helpful to determine the factors that need to be optimized further. These factors can be optimized by using the Sim Runner or another similar software. Hence, experimental design helps to determine the critical value of the factors and reduces the number of experiments for the Sim Runner.

Chapter – 6: Simulation results analysis

The simulation results of five-machine and four-buffer production line are analyzed to determine the effect of the buffer capacities and preventive maintenance on the production line. The factorial plots are presented to see the impact of each factor on cycle time and cost of the system.

6.1 Buffer capacity analysis:

The capacity of buffer has a significant impact on the production output. From the results of the experimental design, one can understand that the buffer allocations have a noticeable influence on the cycle time and the profit of the system. Higher buffer capacity does not guarantee the minimum cycle time and maximum profit in the system.

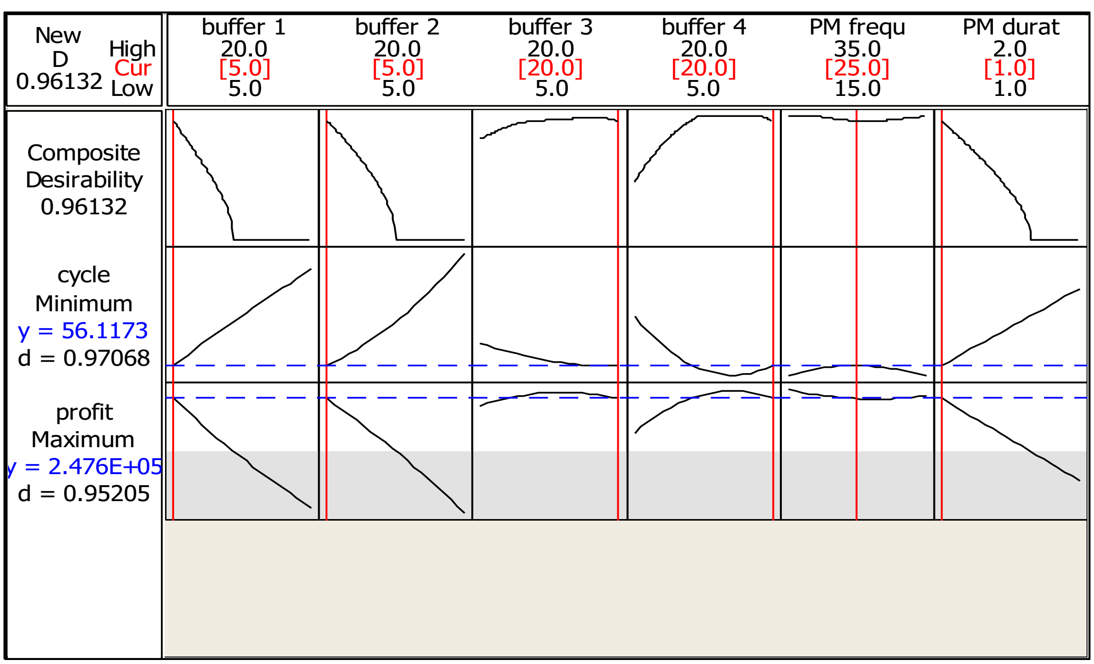

Figure 10: Response surface optimizer graph

Figure 10 represents the response surface graph for the computer remanufacturing line. The red line represents the current value of each factor while the dotted blue line denotes the optimal value of the dependent variables. In the graph, values in red (see square parentheses) the current value of each factor. The values in vertical column with the blue color show the optimal value of the dependent variables (cycle time & profit). Figure 10 shows the optimal desirability is 0.96. Thus, it means there is 96 percent probability to achieve the optimal value of the dependent variables.

From the graph, one can clearly notice that buffer 3 and buffer 4 should have higher capacity to reduce the cycle time. On other hand, buffer 1 and buffer 2 should have minimum capacity because they do not contribute to increase the profit of the system. Buffer 1 and buffer 2 increase the work-in-process in the production line and reduce the production output. Work-in-process does not improve the production rate. Despite getting higher production output, it will increase the holding cost. Thus, every buffer should have the optimal capacity to store the sufficient inventory to continue producing during any accidental failure. As one can see in Figure10, buffer 4 has the biggest impact on the cycle time. If remanufacturing line has smaller buffer capacity for buffer 4 then it reduces the cycle time and the profit of the remanufacturing line. Thus, buffer 4 should have higher capacity to achieve the optimal cycle time. In this case study, the optimal buffer allocation found was 1, 4, 5, and 20 for buffer 1, buffer 2, buffer 3, and buffer 4 respectively. This buffer allocation has minimum work-in process and maximum production output.

To decide the buffer capacity for any production line, user should consider the processing times, failure and repair rates of the machines, and preventive maintenance frequency. These factors are necessary to estimate the buffer capacity for any production line. The experimental design explains the relationship between different buffers and makes the optimization process fast. From the results of the simulation model and ANOVA, user can determine the optimal buffer allocation in a production line.

6.2 Preventive maintenance analysis:

Preventive maintenance is a very important factor in the production line to reduce accidental failure. Different preventive maintenance frequencies are useful to achieve the maximum MTBF. The choice of the best preventive maintenance frequency is essential to reduce the accidental failure without affecting or reducing production output. Moreover, the duration of the preventive maintenance also affects the cycle time. Thus, the relationship between different preventive maintenance frequencies and preventive maintenance durations is crucial to study and understand. The relationship between preventive maintenance frequency and preventive maintenance duration is depicted in Figures 11 and 12.

Figure 11 illustrates the relationship between PM frequency and PM duration when all buffers have the higher value of 20. It is clearly seen that higher capacities of the buffer reduce the impact of the preventive maintenance, as there is very small variation in the cycle time. In addition, higher buffer capacities increase the cycle time with different preventive maintenance frequencies.

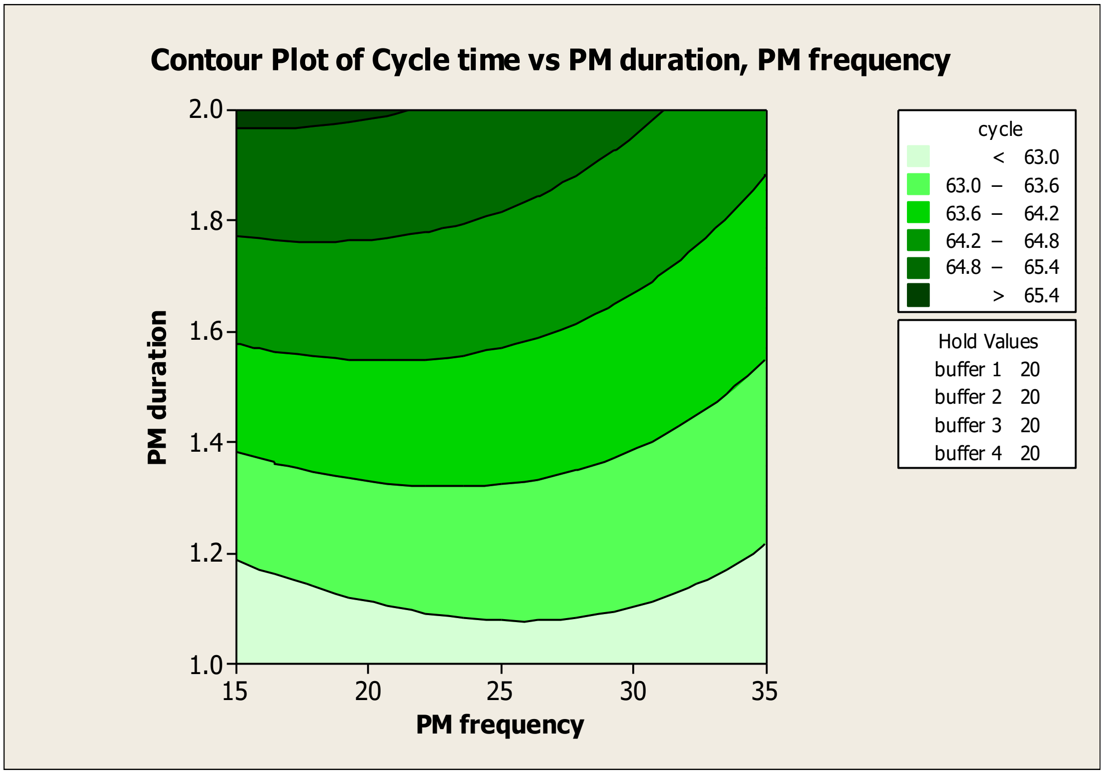

Figure 11: Relation between PM frequency and PM duration

Figure 12 depicts the relationship between PM frequency and PM duration when buffers are held at optimal values, which has been got before optimizing the buffer capacity using the Sim Runner. As can be seen from the graph, PM frequency shows significant variation in the cycle time with optimal values of buffer. Both figures express the expected values of cycle time with different PM frequencies. As a result, both graphs show that less frequent PM is better with different durations. Nevertheless, the best results are noticed with the moderate level of PM. These graphs show the expected value of the cycle time from the analysis of results. Thus, it does not show the optimal value of results. The graphs indicate that less frequent PM is the best option for small and longer duration PM actions. However, the duration of CM action and PM action is a vital factor to decide the frequency of PM.

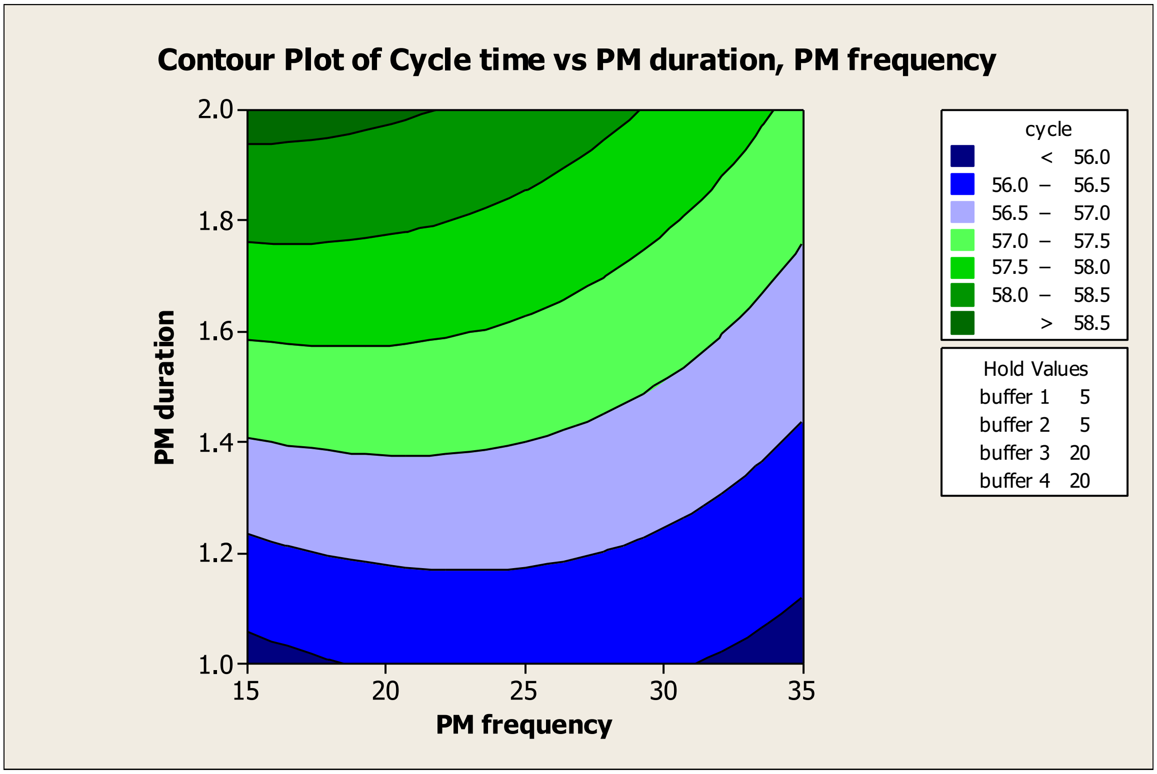

Figure 12: Relation between PM frequency and PM duration

From these graphs, one can conclude that if all machines have same preventive maintenance frequency then it is better to have same capacity for all buffers. Contrary, if all machines have different PM frequency then different capacity for each buffer can be beneficial to reduce the cycle time. Moreover, less frequent preventive maintenance is not necessary to achieve the minimum cycle time. The frequency of preventive maintenance also depends on the time of corrective maintenance.

One of the most important facts is that if one have a small duration of corrective maintenance action, then user can use less frequent maintenance to achieve the optimal cycle time. Production lines with higher repair time will need more frequent PM, because the corrective maintenance action will require a longer time to repair and it will reduce the production output, and if any machine has higher repair time, then it increases the probability of the blocking and starvation. Thus, user should use more frequent preventive maintenance when all machines have higher repair rate. Figure 13 shows the relationship between total maintenance time CM time. X axis represents the repair time, where it shows that if repair time is double or five times more than how it will affect the overall maintenance time. Total maintenance time is calculated for two different PM frequency and for two different PM durations. In this case study, 25-minute frequency is obtained f as an optimal value, which is represented by orange line in the graph. If both CM and PM duration are higher than it is better to use 25-minute frequency. If PM duration is higher and CM duration is small than 35-minute frequency can be used to achieve minimum cycle time.

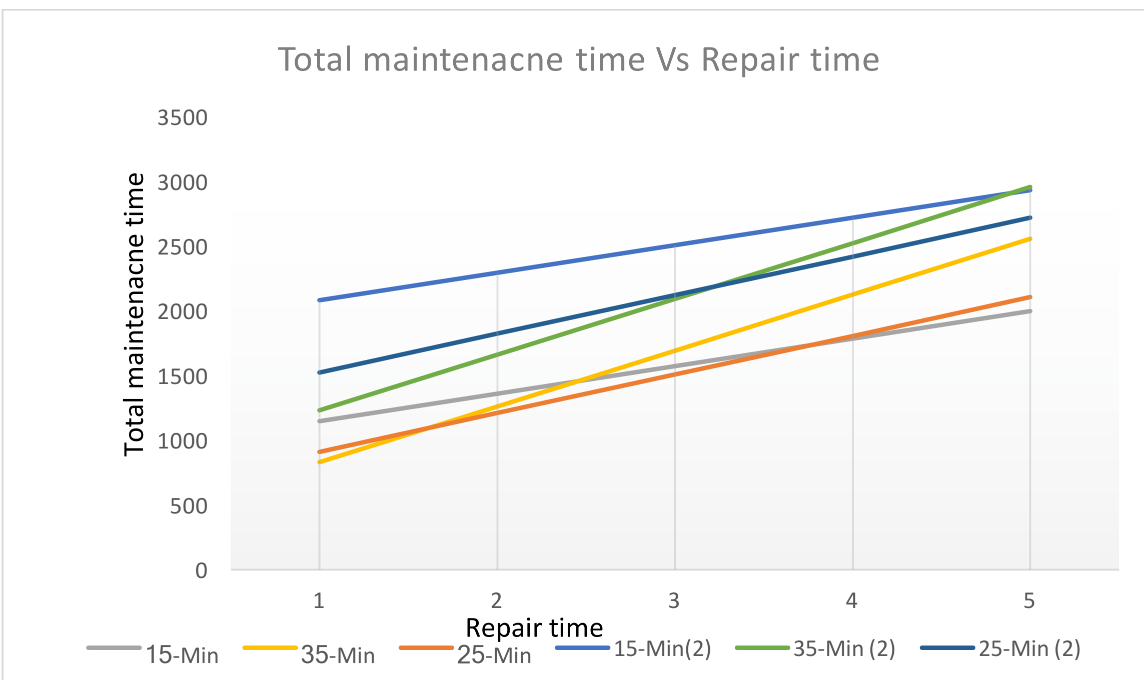

Figure 13: Repair time vs Total maintenance time

The duration of corrective maintenance affects the availability of the machine, which can be represented by following Equation 14, where C is the long-term availability of the machine.

$$C = \frac{MTBF}{MTBF + MTTR} \quad \textbf{(14)}$$

One can notice that any increase in MTTR decreases the availability of the machine. The reduction in availability reduces the uptime of the machine and production output. If some machines have a higher repair rate and some machines have small repair rates, then it is better to use the moderate level PM frequency. The less frequent maintenance strategy can be used while having smaller corrective maintenance time. In conclusion, one should consider the duration of corrective and preventive maintenance action to decide the frequency of the preventive maintenance.

6.3 Factors analysis and optimization:

The factors analysis is accomplished by two methods. The first method is to perform the ANOVA on the results and determine the factors with the greatest impact on the response variable. Table 15 shows that buffer 2, buffer 4 and PM have the greatest impact on the dependent variable. This data is enough to make the optimization decision. The factors that have the greatest influence should be kept at higher levels, and the remaining factors should be optimized. It is the easiest way to reduce the experiment size and optimize the configuration. The second method is to examine the interaction plot between the factors and analyze the effect of each one. Figure 14 shows the interaction plot between factors and cycle time.

The cycle time interaction plot shows that if buffer 1 and buffer 2 have higher capacities, then the remanufacturing line will have maximum cycle time. This graph clearly depicts that the moderate level preventive maintenance strategy has the lowest cycle time when the duration of preventive maintenance is short. The graph illustrates that buffer 4 has a bigger impact than buffer 3. It also shows that if buffer 4 has a higher value, then one can achieve the lower cycle time by keeping the buffer 3 at a lower level. To optimize the cost with the production line configuration, the interaction plot for the various factors and profit is given in Figure 15.

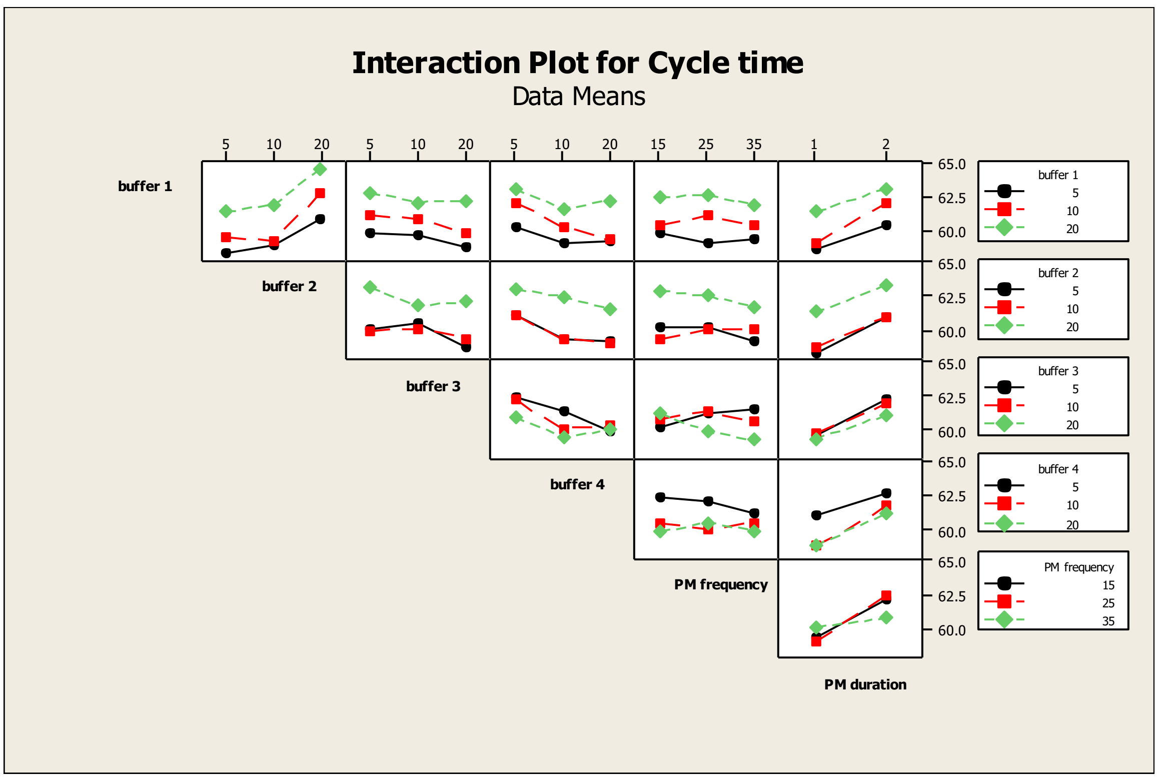

Figure 14: Cycle time interaction plot for five-machine line

The interaction plot for profit denotes that the different preventive maintenance frequencies have the same profit when the duration of the maintenance action is short. Still, if one analyze the graph very carefully, then one can see that the moderate level of PM has a slightly higher profit than other two maintenance levels. In addition, buffer 1 and buffer 2 capacities are highly responsible for the reduction in production and these factors decreases the profit as well. On the other hand, a small capacity of buffer 3 maximizes profit. By comparing both graphs, user can make the decision to get the optimal configuration of the production line. So, the optimal configuration can be attained by keeping buffer 1, buffer 2, and buffer 3 at lower levels, whereas buffer 4 should be held at a higher capacity level. By comparing both graphs, the moderate level PM strategy is selected for the production line. Therefore, experimental design is useful in understanding the effect of each factor and to find the optimal configuration of the production line.

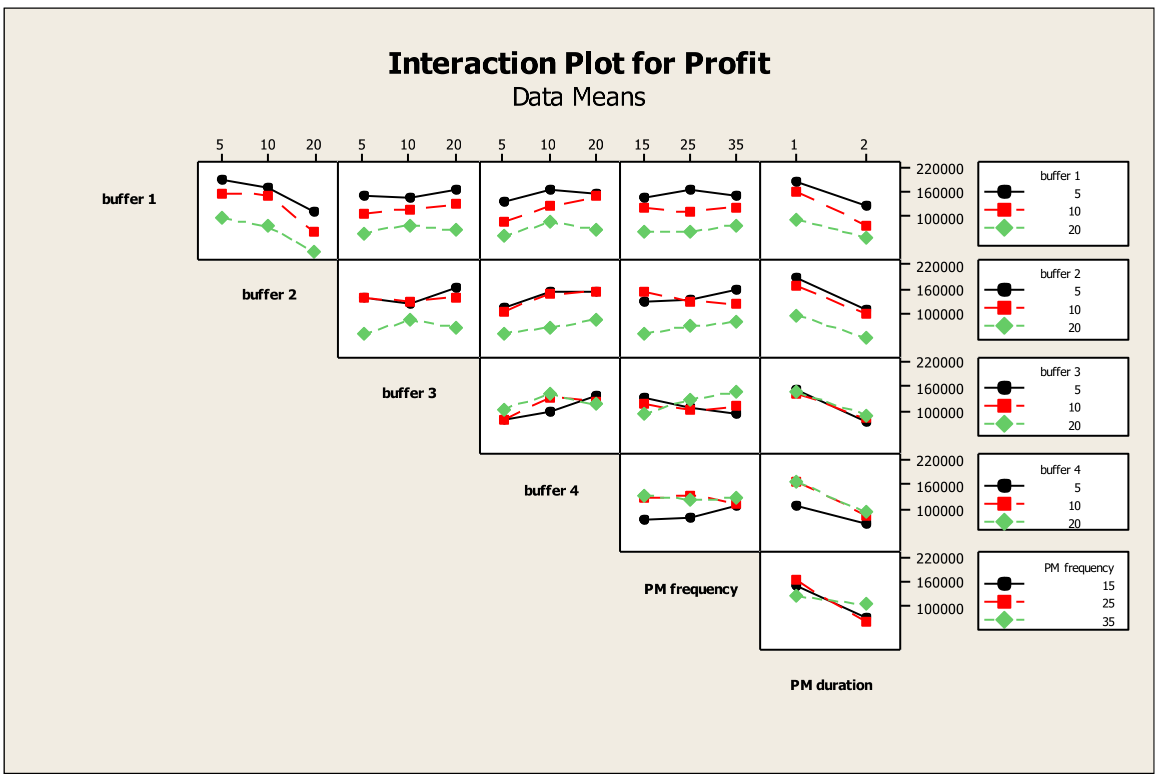

Figure 15: Profit interaction plot for five-machine line

This chapter shows how different buffer allocations and different preventive maintenance policies can play a vital role in achieving higher production. The relationship between PM frequency and PM duration can be helpful to decide the suitable PM policy for different buffer allocations. Moreover, the duration of the corrective maintenance is also a crucial part in deciding the preventive maintenance. The frequency of the PM should be selected by analyzing the duration of the corrective maintenance. By plotting the interaction plot for the profit and cycle time, user can identify the crucial factors and decide the best configuration of the production line that will increase the production output.

Chapter – 7: Conclusion and Recommendations

Up to now, the shared methodology to apply maintenance is based on the failure rate and cost of the system. All the research works have been done to find the optimal JIT during different maintenance actions. These published works do not explain the change in MTBF due to change in preventive maintenance frequency. They found the optimal buffer inventory and optimal preventive maintenance frequency, which have minimum cost. However, the issue of optimization of the buffer allocation and preventive maintenance is not studied. Buffer capacity and the frequency of the preventive maintenance are indirectly linked with each other. Any production line can improve its production rate by optimizing the buffer capacity with the preventive maintenance frequency.

This study applies a simulation-based experimental methodology to determine the most influential factor in the production line. Moreover, this study explains the effect of different preventive maintenance frequency on the MTBF and production of the system. Allocation of buffer capacities performs a vital factor in the production line. Thus, it is necessary to estimate the effect of different buffer allocation and different preventive maintenance frequency to get the maximum output from the system. Experimental design is applied in this study to explore the impact of individual factors on the cycle time of the production line. This methodology will help to determine the optimal combination of buffer allocation and preventive maintenance frequency by reducing the work in process and accidental failure.

In conclusion, this research represents that, how one can obtain the optimal buffer capacity and preventive maintenance frequency by using simulation and experimental design. The case studies have proved that the simulation-based experimental methodology can help to achieve economical and faster configuration of the production line. This methodology can be applied to any real production line to achieve the maximum output by defining the best buffer allocation and preventive maintenance strategy.

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APPENDICES

Appendix A: **Interaction plots for nine-machine production line.**

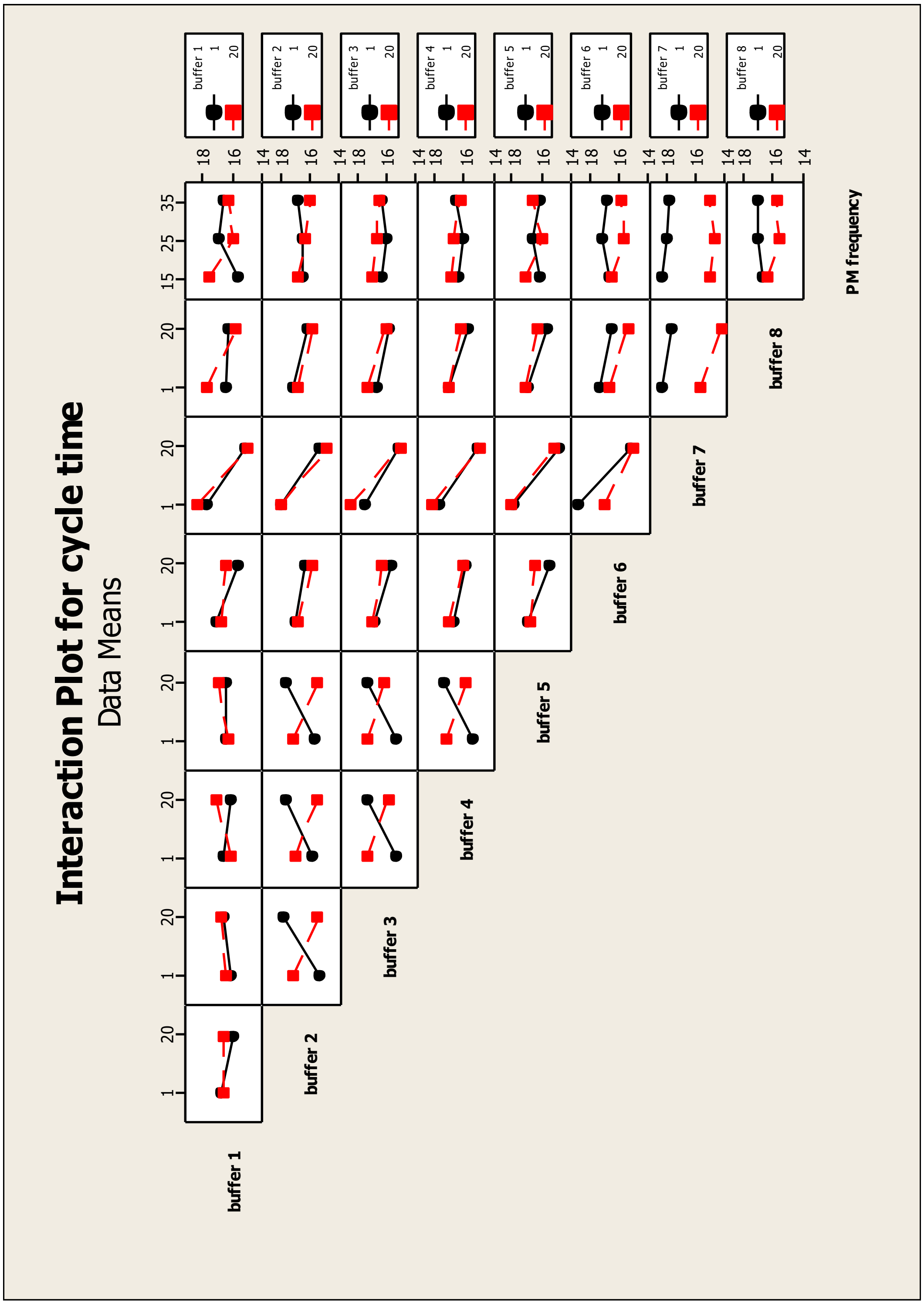

Figure 16: Cycle time interaction plot for nine-machine line

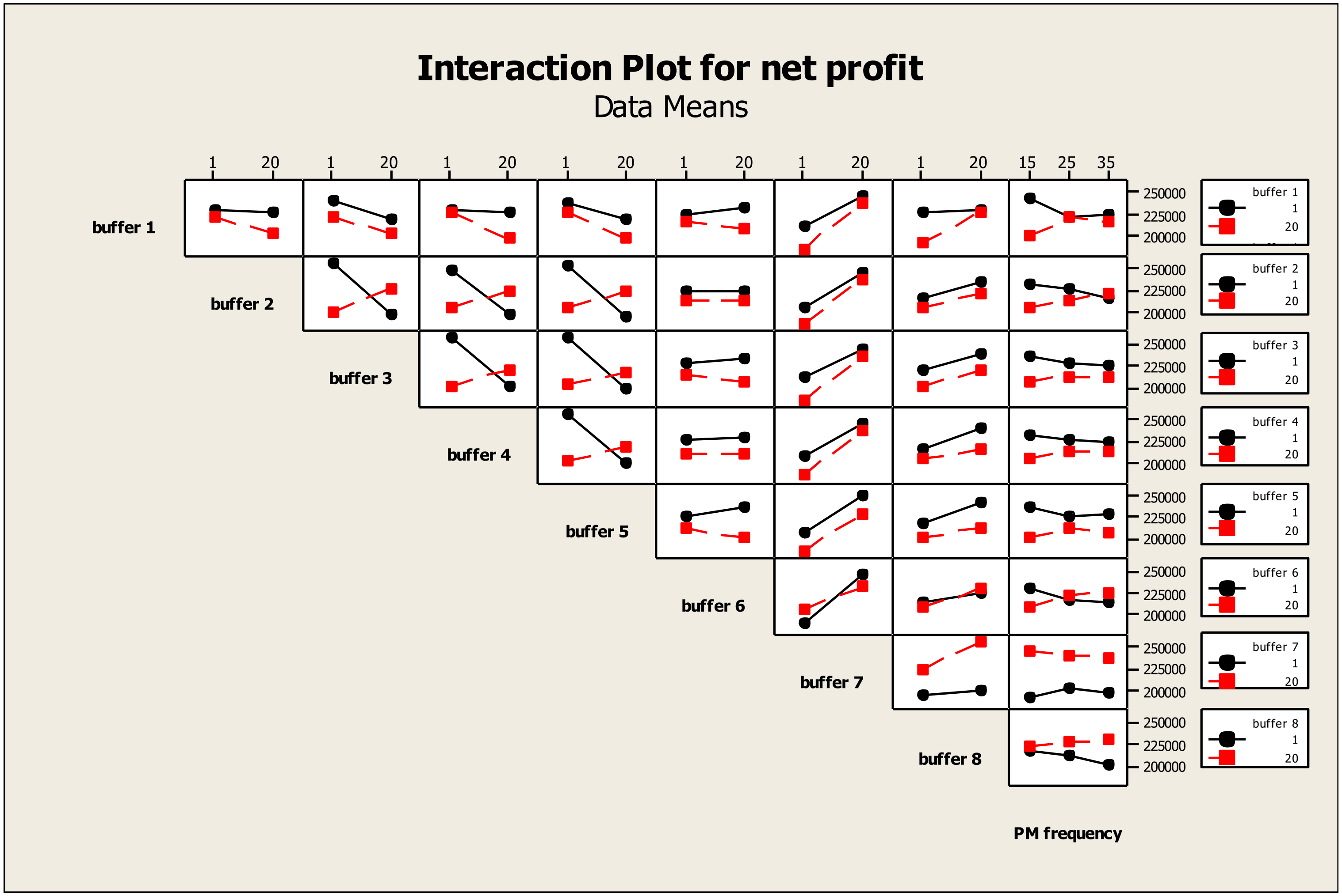

Figure 17: Profit interaction plot for nine-machine line

Appendix B: Calculation of number of Replications

Multiple replications of the simulation model are necessary to ensure that the results are noted within the 95% confidence interval. The base model was run for 10 replications and different random numbers were used to calculate the number of replications. Significance level is 0.05 for this experiment. To make sure that the cycle time will not vary more than 0.25 hour from the true mean, acceptable error level (e) was selected 0.25 hour. Calculations showed that 10 replications are needed and the calculations are given below:

Formula:

$$N = \left(\frac{t_{n-1, 1\text{-a}/2} s(n)}{e} \right)^2 \qquad \textbf{(15)}$$

Where,

N = Number of model replications

S(n) = point estimate of standard deviation based on n model replication

e = error amount

The base model was run for 10 replications and mean of each replication was calculated as shown in the Table 27. Base model has 10 replications. Therefore, value of t was chosen from the t-distribution table. For the 10 replications, t value was found 2.262 from the t-distribution table. Standard deviation was found 0.33 by calculating the mean and variance for the results. The obtained values were substituted in above equation:

$N = (2.262*0.33/0.25)^2 = 10$

The results of the 10 replications are shown in the table 27. Table 27 also shows the calculations of mean, variance and standard deviation.

Table 26: Calculation of standard deviation and variance

Replication No	**Cycle time (hours)**
1	62.35125
2	62.50174
3	62.69856
4	62.70733
5	62.73016
6	63.00719
7	63.02669
8	63.07816
9	63.18313
10	63.4516
average	**62.87358**
Standard deviation	**0.333**
Variance	**0.111**

Appendix C: **Discrete event simulation and ProModel software**

Discrete event simulation:

Discrete event system simulation is the modeling of system in which the state of a variable changes only at a discrete set of points in time. A discrete-event simulation (DES) models the operation of a system as a discrete sequence of events in time (Banks et al.,2005). Each event occurs at an instant in time and marks a change of state in the system. Between consecutive events, no change in the system is assumed to occur; thus, the simulation can directly jump in time from one event to the next. The simulation models are analyzed numerically rather than analytically methods. Analytical methods employ the deductive reasoning of mathematics to solve the model. Numerical methods employ computational procedures to solve mathematical models. In case of simulation models, which employ numerical methods, models are run rather than solved. An artificial history of the system is generated from the model assumptions, and observations are collected to be analyzed and to estimate the true system performance measures. Real world simulation models are rather large, and the amount of data stored and manipulated in vast, so such runs are usually conducted with the aid of a computer. To study any system with simulation, one should follow the steps given below

1 Problem formulation
2 Setting of objective and overall project plan
3 Model conceptualization
4 Data collection
5 Model translation

6 Verification

7 Validation

8 Experimental design

9 Production runs and analysis

10 More experiments

11 Documentation and reporting

12 Implementation

ProModel software:

ProModel is a discrete-event simulation software that is used to plan, design and improve new or existing manufacturing, logistics and other operational systems. It empowers the user to accurately represent real-world processes, including their inherent variability and interdependencies, to conduct predictive analysis on potential changes. The software is easy to use and flexible with animation capabilities. ProModel provides ease to focus on issues such as resource utilization, system capacity, productivity, and inventory levels. ProModel has virtually unlimited size and simulator offers a 2D/3D graphics editor with scaling and rotating. ProModel has programming features within the environment, and the capability to add C or Pascal type subroutines to a model.

Appendix D: Sim Runner

Sim Runner is a built-in optimization suite in ProModel simulation software. Sim Runner takes existing ProModel models and evaluates them and suggests best ways to achieve the desired results. One can conduct the what-if analysis on real world process. Sim Runner runs sophisticated optimization algorithms on model to optimize multiple factors.

Sim Runner uses both genetic and evolution strategies algorithms. However, its primary algorithm is evolution. The specific design of these algorithms for Sim Runner is based on the work of Bowden (1998). An evolutionary algorithm is a numerical optimization techniques based on simulated evolution. To validate the results, one must need an objective function. If the returned value falls within the acceptable range then Sim Runner will continue searching for the optimum; otherwise it will reject the value and search for another value. By using, genetic and evolution algorithms, Sim Runner optimizes the experiment with ease and saves time. Figure 18 summarizes the search process. At the beginning, Sim Runner will determine the altitude of each variable with current value and then it will send all variables in different direction to see the response of each variable on the objective function. Sim Runner will follow the same process for few runs and then it will compare the results with each value to determine the direction in which to proceed for optimization.

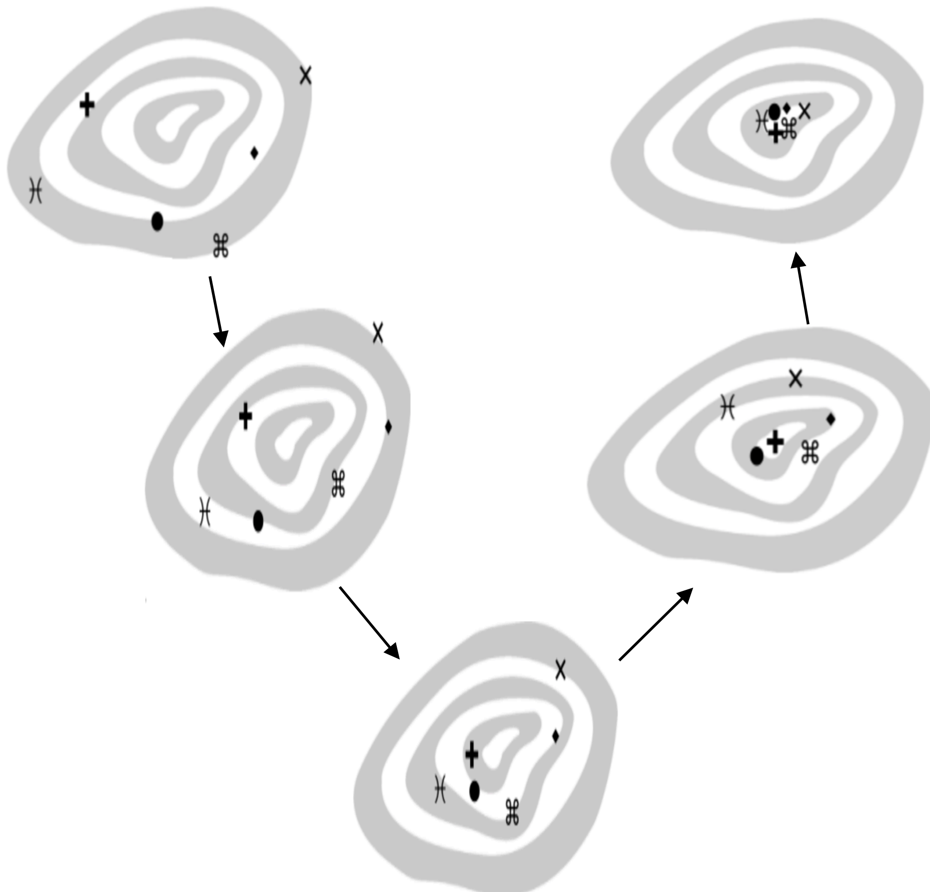

Figure 18: Sim Runner search process

In next step, it will take the average of objective function and if the average of objective function is increased then it proves that the program is going in the right direction. Once the average of objective function is equal to the best in the group, one can say that the program has converged to the optimal value for each variable. This way Sim Runner uses both genetic and evolutionary algorithm and to optimize the problem.

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