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Original Research Article

Optimising System Continuity in Preventive Maintenance Schedules Based on Integrated Failure Mode and Spare Part Inventory Modelling

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Abstract

Systems with multiple components and various configurations are classified as complex. Unless failure modes are carefully considered, the replacement of components or breakdown can lead to the shutdown of the whole system. Because of this, maintaining a complex system output can be challenging, especially if the right preventive maintenance schedule is not determined. In order to support replacement activities, a sufficient supply of spare parts is required. Based on the failure mode identified and effects analysis, this research presents an integrated preventive maintenance scheduling methodology for complex systems. Components and subsystems in the system can be modelled, such that failures in different parts of the system can be predicted based on expected life. To maintain a high level of production during PM, the need to analyse failure modes that result in only partial system failures is necessary. For determining the required number of spare parts, we factor in preventive replacements for each FMEA block. Optimal replacement intervals and spare part quantities are determined using the genetic algorithm. In order to demonstrate the application of the proposed method, numerical experiments are conducted. The developed method in this paper not only improves system reliability and minimises costs but also maintains the continuity of system outcomes during replacement activities.

Keywords: Preventive Maintenance Optimisation; Failure Modes and Effects Analysis (FMEA); Continuity of system output; Spare Parts Inventory; Partially Failure Modes.

1. Introduction

In order to improve the availability of complex systems and reduce their maintenance costs, preventive maintenance optimisation is an effective method [1]. When an unexpected system failure occurs, production will be negatively impacted. There are many failure modes in a complex system. Failure modes vary depending on the configuration of nonidentical components and subsystems in the system. Some failure modes do not need complete stoppage of the system, but there are also a good portion of failure modes that require switching off the system for urgent repairs. Hence, if failure modes are not evaluated and identified, maintenance activities could not be planned properly, resulting in the shutdown of the entire system and causing significant maintenance costs. Therefore, preventive maintenance (PM) should be developed for complex multi-component systems, taking into account failure modes.

Performing maintenance requires sufficient number of spare parts in inventory. To ensure the system's availability and meet maintenance requirements, spare parts must be available [2]. In practice, however, spare parts stock is limited due to lengthy delivery times. The possibility of stock-out when spare parts are required is high and causes more complication to the system [3]. However, combining spare parts inventory and failure modes in maintenance planning is difficult [4]. One of the main reasons is the lack of reliability data and system performance indicators, without these the model for ensuring continuity of system cannot be established.

This paper uses a well established failure mode and effect analysis (FMEA) model and corresponding data on components reliability to support a method that determines the optimised preventive maintenance intervals and spare parts inventory for ensuring the continuity of complex system outcomes. The failure of different components of a system can be estimated from their life expectancy when the system is modeled as a series and parallel arrangements consisting of subsystems and components. To maintain a high level of production during PM, the need to analyse failure modes that result in only partial system failures is necessary. For determining the optimal number of components (spare parts), preventive parts replacement for each FMEA block should be factored into the system. The developed method in this paper not only improves system reliability and minimises costs, but also maintains the continuity of system outputs. The integrated approach can be easily applied to any replacement scheduling problem and spare parts inventory in any complex system process.

2. Literature Review

Maintenance is one of the most effective ways to reduce downtime and increase availability for complex systems. Several maintenance optimisation strategies focusing on preventive and corrective maintenance have been developed in reliability research. When a system fails, corrective maintenance must be performed. It can be dangerous and costly for a system to fail during operation [5]. This makes it an inappropriate strategy for maintaining complex systems. System components can then be maintained through a preventive maintenance strategy. The system should be scheduled in advance so that failures can be avoided and maintenance costs can be reduced [6]. A complex system consisting of multi-components can be planned using various standard methodologies, including group and block replacement methods. The block replacement strategy involves replacing a group of components regularly. According to Chiu et al. [7], system components can be maintained in groups to reduce maintenance costs.

2.1 PM Planning for Continuity

Maintenance activities often result in discontinuities in system outcomes in manufacturing systems. The system should run continuously, with minimal downtime, to ensure continuous operation [8]. There have been several publications dealing with preventive maintenance strategies based on failure modes for complex systems. In their study, however, spare parts inventory level is not considered. Furthermore, replacements require an entire system shut down for maintenance. For example, an optimisation framework and a statistical approach for selective maintenance are presented by Ruiz et al. [9] to maintain a complex system with multiple failure modes. In their study, the hazard rate for each failure mode is modelled as a function of the degradation level for the same component in order to model the dependency between failure modes. In order to minimise maintenance costs while maintaining high system availability, Liu et al. [10] found the optimal group maintenance strategy for multi-component systems with multiple dependencies. Analysis of failure dependence is used to establish the system reliability model. Considering parallel systems with two failure modes, Peng et al. [11] proposed three maintenance policies. Each component is regularly inspected to determine its state. The system fails when its components fail or are being maintained.

2.2 Considering Inventory Level

In the previously mentioned studies, spare parts are assumed to always be available and sufficient for maintenance optimisation for manufacturing systems. In engineering practice, this is obviously restrictive. A preventive maintenance schedule for a group of components should take into account the availability of spare parts and inventory requirements of a system. In order to reduce system downtime and increase availability, spare parts need to be provided on time [12].

Spare parts ordering strategies based on maintenance have been discussed in a number of publications and literature reviews. Most maintenance strategies, however, assumed that the system should shut down during replacement. Panagiotidou [13] presented two approaches for ordering spare parts. In both approaches, spare parts order and maintenance policies are combined to optimise spare parts ordering. By examining block replacement and periodic inventory reviews, Jiang et al. [14] discussed an optimisation problem for multi-unit systems with inventory deterioration. The series unit of the system uses several identical components, and when one of these components fails, the system is significantly degraded. Another study based on the ordering quantity and the ratio of the ordering interval to preventive maintenance interval, Siddique et al. [15] developed an optimisation model for planning the maintenance and spare parts inventories of a multi-component system. Recently, an optimisation strategy combining maintenance and spare inventory was investigated by Zhang et al. [16] for series and parallel systems based on failure modes. Spare parts supply was not addressed based on understanding system behaviour and identifying failure modes in most studies. For example, to provide spare parts for multiple items with random breakdowns. Defining the right maintenance time and managing spare parts inventories are necessary to minimise expected average costs. The critical components are affected by software failures, which cause the system to stop working completely.

A variety of planning methods have been examined in previous studies. The strategies were implemented in order to meet specific performance targets. In spite of this, application to the real industrial world remains a challenge. Since most approaches are stochastic, the underlying causes of system failure are not considered. The severity of the failures was considered insignificant and could be rectified with regular maintenance. This statement is not always valid when complex systems are considered. An integrated approach with failure modes well defined and probability of spare parts stock-out is required.

2.3 Identification of Failure Modes

A failure occurs when a system is unable to perform a required function [17]. The identification of failure modes and their effects on a system is essential for determining functional failures. This serves as a visual representation of what happens when a failure mode occurs [18]. For this, a systematic method for evaluating system processes is required. The FMEA method can identify potential failure modes in a system by reviewing as many components and subsystems as possible. The major purpose of this method is to analyse systems and identify potential failures before they occur so that preventive maintenance can be planned and scheduled [19].

2.4 Combination of FMEA and Inventory

Maintaining continuous system outcomes is possible through a preventive maintenance strategy based on understanding system behaviour and identifying failure modes. In this way, preventive maintenance can be optimised based on failure modes that enable the system to function properly during the execution of preventive maintenance activities. Furthermore, it has the potential to significantly reduce costs, in addition to reducing failures and enhancing reliability.

An extensive amount of research has been conducted on evaluating failures, optimising preventive maintenance and spare part problems by employing FMEA. However, studies assumed that systems should be stopped working when maintenance activities start. Based on engineering analysis, Qian et al. [20] proposed a method for predicting spare parts consumption. Using FMEA tables and parameters in the equipment design process, the paper determines the method of calculating the number of overhaul repairs for equipment units. To determine the optimal spare part inventory for a system with multiple identical components, Ferdinand et al. [21] presented an algorithm based on failure mode and effects analysis. Based on a detailed analysis of components of the systems, risk priority number (RPN), their study aimed to identify and assess systems default risks relevant to availability. Similarly, a model based on inventory cost and spare part availability was developed by Lukitosari et al. [22] in order to arrive at the best choice. For determining risk priority (RPN) and critical spare parts to stock, the failure mode and effect analysis (FMEA) tool were used. Gong et al. [23] developed a framework for dealing with the problem of spare parts management based on Failure Mode Effect and Criticality Analysis. In their methodology, the risk priority number and criticality were used instead of the failure rate. With the age replacement model combined with failure mode and effect analysis and preventive maintenance, Purwanggono and Ibana [24] proposed a maintenance plan for CNC milling machines.

According to the above studies, the planning of maintenance and spare based on risk priority assessment by FMEA. It is logical to apply FMEA to determine RPN in order to manage risks [25]. However, from the manufacturing system's perspective, continuity of operation is more important than management of risk. Therefore, understanding and making use of the failure modes for sustaining operational continuity is considered a missing link in literature.

In a recent study using the FMEA block concept [26], continuity of the production system was enhanced. The study integrated preventive replacement intervals which were determined by failure distribution computation of critical components. The study was later extended by analysing the system's reliability with the Weibull failure-time distribution [27]. However, the spare parts inventory policy was not considered in either studies.

2.5 Summary of literature review

The literature review identifies several issues that prevent current preventive maintenance regime to be effective.

1. The failure modes identified by FMEA are used for risk prioritisation purpose. Literature reviewed so far were only able to recommend optimisation of complete shutdown of the system.
2. Due to (1), algorithmic formulation using FMEA outcomes for maintenance purpose is not available in literature.
3. No literature has considered the effect of performance of spare parts suppliers such as lead time, parts quality and price. Hence, the ordering strategy is not reflecting critical issues in preventive maintenance such as service life of new spare parts.

This paper develops an integrated PM scheduling methodology that could maximise continuity of operation of the manufacturing system. A real life case study will be used to illustrate effectiveness of the methodology.

3. System Analysis

The purpose of this section is to introduce the concept of maintenance and spare parts policies, as well as the standard assumptions and definitions that are usually used for introducing these concepts.

3.1 Description of System Maintenance and Inventory Policy.

The focus of this paper is to ensure continuous outputs for CNC system (comprised of n nonidentical components) during preventive replacement activities. The system is modeled as a series and parallel arrangements consisting of subsystems and components. Preventive replacement is performed according to an FMEA block-based approach. The failure rate of components increases over time due to wear-out. According to this, all components must be replaced at the same time in accordance with the block PM interval *T*. Whenever a preventive replacement action is performed for any block; the entire system is not shut down completely. All components are restored to their original condition after each replacement and are immediately replaced if they fail. In other words, during maintenance, the rest of the system continues to operate.

When spare parts have not been planned, preventive maintenance can be delayed, resulting in high operating costs and unexpected. As a result, a high downtime cost will result from the system being down while waiting for the spare parts. Having spare parts on hand is, therefore, essential. The optimal replacement times for each FMEA block are used to develop an inventory management plan. When stock levels fall to a reorder point s, an order of spare parts O_C is placed. In every FMEA block replacement cycle, stock levels are continuously reduced. After a lead time, the order quantity is delivered. An inventory profile is illustrated in Figure 1 for each FMEA block of a system.

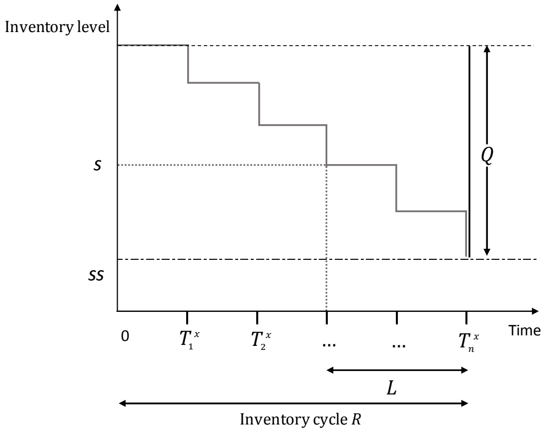

Figure 1. Inventory Policy

3.2 General Assumptions

The following assumptions are made in order to limit the problem's generality. The presented models will be discussed in relation to these essential points.

- The operation time is measured in hours.
- All CNC system components are new at the start ($t = 0$).
- After preventive replacement, the system is as good as new. Based on renewal theory and generally used in maintenance literature.
- There is a general observation and common experience in the industrial system that failure replacements are more costly than preventive replacements. *CM* > *PM*.
- The order quantity of each FMEA block is delivered all at once.
- Ordering costs vary by supplier and are fixed.
- Within the inventory cycle, lead time is a constant value $L < R$. Where inventory cycle is $R = T * in\left(\frac{t}{T}\right)$.

3.3 Failure Distribution

Preventive maintenance activities can increase the reliability of systems. Prior to scheduling a preventive maintenance program, reliability must be mathematically expressed. An analysis of system reliability using the Weibull distribution method is presented in this section. In general, Weibull distributions describe failure patterns that can be fitted by adjusting their parameters. According to maintenance literature, this is the most common assumption [28]. The two-parameter Weibull probability density function *f(t)* is given as:

$$f_i(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (1)$$

This formula considers t, the service life of the system component, as well as β and η, the parameters of shape and scale parameters. Probability of some component failing before a given time t is represented by a cumulative distribution function. This leads to the following function:

$$F_i(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (2)$$

where β and η denote the shape and scale parameters (hours), respectively. Hence, the reliability function is the probability of the component surviving until the end of time *t*, and it is given by:

The reliability of a component is the probability that it will perform its intended function for a specified period of time, and it is given by:

$$R_i(t) = 1 - F(t) \qquad (3)$$

This defines,

$$R_i(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \qquad (4)$$

The Weibull hazard rate function measures the probability of a component suffering a failure per unit of time. Hazard rate $h_i(t)$ associated with components is related to their use time during operation. It can be expressed as follows:

$$h_i(t) = \left(\frac{\beta}{\eta}\right) * \left(\frac{t}{\eta}\right)^{\beta-1} \qquad (5)$$

3.4 Maintenance Planning

Through the determination of an optimal interval for preventive maintenance (Block replacement policy), the expected cost for a component per unit of time is minimised. Renewal functions, although simple, depend on mathematical expressions that can often be complex to determine [29]. In complex systems, it is not sufficient to replace one component at a time to maintain the system. In addition to the difficulty of replacing a group of different components. Thus, the cost of maintaining the CNC system containing nonidentical components is calculated using a mathematical matrix model based on the FMEA Block method. At regular intervals, each FMEA block's components will be replaced. The objective of our work is to make sure that a system remains operational during the replacement process at the lowest possible cost. All different components must be replaced simultaneously in order to calculate the overall maintenance replacement cost per block.

Preventive replacement is performed with a cost **PM** > 0 if the components are still operating at *T*. Corrective replacement of failed components before *T* is carried out by replacing them with a higher-cost component **CM** > 0. The replacement process is both perfect and instantaneous when it comes to preventative and corrective replacement. Furthermore, the components' failure up to the replacement time incurs an extra cost of lost production **PLs**.

The cost of the maintenance is calculated by using the first statement **PM,** during interval *T*, to obtain good as new components. When components need to be replaced as part of preventative maintenance, downtime costs are incurred. Labour costs, labour time PR_{time}, and the number of laborers needed PN are all factors that must be considered when replacing components.

$$\mathrm{PM} = \mathrm{PC}\ .\ \mathrm{PN}\ .\ PR_{time} \qquad (6)$$

The **PC** value is a matrix of column $n \times 1$ representing the person's cost per hour. The values of PN and PR_{time} are constant.

During the interval (0, T), F(T) indicates an expected failure time based on the Weibull distribution. The diagonal matrix can be expressed as follows:

$$\mathbf{F}(\mathrm{T}) = diag \begin{bmatrix} 1-e^{-(\frac{T}{\eta_1})^{\beta_1}} & 0 & \dots & 0 \\ 0 & 1-e^{(\frac{T}{\eta_2})^{\beta_2}} & \dots & 0 \\ \vdots & \vdots & \ddots & \\ 0 & 0 & & 1-e^{(\frac{T}{\eta_n})^{\beta_n}} \end{bmatrix} \qquad (7)$$

The potentially catastrophic costs associated with unplanned component failures must be considered when considering future periods of operation for the system. Replacement of failed components is known as correction maintenance (**CM**). Equation (8) describes the costs of components, labour, downtime, and shutdowns, respectively:

$$\mathrm{CM} = (\mathrm{S} + \mathrm{LC} + \mathrm{DTC} + \mathrm{SH}) \qquad (8)$$

Where a $n \times 1$ column matrix represents the component cost variable as follows:

$$\mathrm{S} = \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ \vdots \\ s_n \end{bmatrix} \qquad (9)$$

When system components are first put into operation at $T > 0$, they are susceptible to unexpected failures. In the event that a component fails, replacing it will be necessary since it will affect other components. In the event of component failures during production, downtime **DTC**. The cost of lost production **PLs** ($n \times 1$) is also included, as well as the cost of replacement time CR_{time}, and labour costs **LC**. The following formulas can be used to calculate labour costs and downtime:

$$\mathrm{LC} = \mathrm{P}\ .\ C\ .\ CR_{time} \qquad (10)$$

In this matrix, C represents the hourly cost of a worker, which is a constant value, while **P** represents how many workers are represented in the $n \times 1$ column matrix and, therefore:

$$\mathrm{DTC} = \left(\begin{bmatrix} PLs_1 \\ PLs_2 \\ PLs_3 \\ \vdots \\ PLs_n \end{bmatrix} .CR_{time} \right) + \mathrm{LC} \qquad (11)$$

In some cases, some system components may be affected by a shutdown because of their dependency. For example, it is possible for the entire FMEA block to fail if just one component fails in a series configuration.

When one component fails, the Y matrix is affected. The rows of the matrix are used to explain the system components. For instance, row -1 represents component A, row -2 represents component B, and so on. Each row represents a component within the schema. The impact of the failure of a component on other components is indicated by columns of the matrix. The value one is assigned to a failure component; otherwise, zero is assigned. This can be obtained by the following formula:

$$\mathrm{Y} = w^{(i)(y)} \qquad (12)$$

Since one component failing does not affect itself, the diagonal elements of matrix w have zero values. Since one component failing does not affect itself, the diagonal elements of matrix w have zero values. If the failure of i^{th} components affects y^{th} components, then the matrix elements will take the value 1. Otherwise, it will take the value 0. In this way:

$$\mathrm{PLr} = \mathrm{Y}\,.\,\mathrm{PLs} \qquad (13)$$

For y^{th} component, production loss is represented by **PLr** per hour. As for the rest of the components, **SH** represents the shutdown cost. Calculating **SH** can be accomplished using the following formula:

$$\mathrm{SH} = \begin{bmatrix} PLr_1 \\ PLr_2 \\ PLr_3 \\ \vdots \\ PLr_n \end{bmatrix}\ .\ CR_{time} \qquad (14)$$

Denote $M_{cost_b}(T\ )$ as the total maintenance cost for each FMEA block. The model can be calculated from the previously formatted equations as follows:

$$M_{cost_b}(T\ ) = \Big[\Big[\mathrm{PC} * PN * R_{time} * in\left(\frac{t}{T}\right) \Big] + \Big[\big(\mathrm{F}\,(T\ )\,(\mathrm{S} + \mathrm{LC} + \mathrm{DTC} + \mathrm{SH})\big) * in\left(\frac{t}{T}\right) \Big] \Big] \qquad (15)$$

Where in is the integer part of $\left(\frac{t}{T}\right)$.

3.5 Economic Order Quantity for Spare Parts

The availability of spare parts when a system requires maintenance is crucial to ensuring its continuity. One of the most effective ways to avoid unplanned downtime is to determine the necessary spare parts based on system reliability and maintenance characteristics. Spare parts demand is generated based on maintenance activities information. The number of spare parts required for an inventory can be estimated once the details of FMEA block replacements and reliability have been determined.

To achieve this, the frequency of component replacements during operation period cycle length t, whether preventive or corrective, is used to determine the expected spare parts annual demand d_i for each component *(i=1,2,,,n)* in FMEA block (*b=1,2,,B*). As such, it can be described as follows:

$$d_i = in\left(\frac{t}{T}\right) + \left[F(T) * in\left(\frac{t}{T}\right)\right] \tag{16}$$

Spare parts delivery is not constrained at this stage since the lead time is not affected by order size. Therefore, the lead time rate L_r is calculated by dividing the exact lead time of the order to be delivered L by the inventory cycle *R*. This can be expressed as follows:

$$L_{\boldsymbol{r}} = \frac{L}{R}, \quad 0 < L < t \tag{17}$$

During a maintenance interval, all components in every block are replaced simultaneously. A complex system often requires ordering different spare parts from different suppliers. The reason is that ordering them from the same source would be incoherent. In this study, components suppliers for each FMEA block are assumed to be arranged according to sets. Using each set coming from a different supplier $\mathbf{DS}_p$, the expected annual spare parts demand for a block $\mathbf{D}_{\mathrm{B}_b}$ can be expressed as follows:

$$\mathrm{D}_{\mathrm{B}_b} = \left[\mathrm{DS}_1 + \mathrm{DS}_2 + \mathrm{DS}_p\right] \tag{18}$$

where,

$$\mathrm{DS}_p = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ d_n \end{bmatrix} \quad , p = 1,2 \ldots P \tag{19}$$

For each set in one FMEA block, Equation (20) shows the expected demand during lead time $\mathbf{ED}_{\mathrm{B}_b}$. Using the transpose, an equation can be simplified that can be solved with the lead time after the product of a $n \times 1$ column matrix $\mathbf{D}_{\mathrm{B}_b}$ is obtained. First matrix columns should equal second matrix rows. Therefore, it can be stated as follows:

$$\mathrm{ED}_{\mathrm{B}_b} = \left[\mathrm{DS}_1 + \mathrm{DS}_2 + \mathrm{DS}_p\right]^T \begin{bmatrix} L_{r_1} \\ L_{r_2} \\ \vdots \\ L_{r_n} \end{bmatrix} \tag{20}$$

3.5.1 Shortage Cost

The number of replacements that will occur during inventory cycle *R* can be predicted. *R* is, therefore, equal to the sum of preventive replacement intervals determined within one inventory cycle. Based on the distribution function of the number of replacements during lead time, the expected shortages per cycle and the safety stock are calculated. The following formula can be used to determine the number of shortages expected per cycle:

$$C_{sh} = z \cdot \left[\frac{\left[\mathbf{DS}_1 + \mathbf{DS}_2 + \mathbf{DS}_p\right]^T \begin{bmatrix} L_{r_1} \\ L_{r_2} \\ \vdots \\ L_{r_n} \end{bmatrix}}{Q}\right] \tag{21}$$

Loss of production can result from the unavailability of spare parts. Usually, parts have to be replaced at random intervals during failure tasks. Therefore, the probability distribution can be used to model the number of spare parts during the lead time due to the uncertainty regarding the time of failure. Therefore, the probability of failure during lead time can be expressed as follows:

$$P(t = L) = \left(1 - e^{-\left(\frac{L}{\eta_i}\right)^{\beta_i}}\right) \tag{22}$$

Safety stock ss should be considered to avoid a shortage of spare parts during the lead time. During the lead time, safety stock is issued based on predicted failure numbers with respect to how many components are used x. Therefore:

$$E_i = x + \left(1 - e^{-\left(\frac{L}{\eta_i}\right)^{\beta_i}}\right) \tag{23}$$

The E_i will differ for each component within the same block due to the different lifetime distributions of the components. Therefore, safety stock can be determined by the sum of E_i values in the FMEA block, which is the number of components used over the period of lead time. Equation (23) can therefore be rewritten to give Equation (24) as follows:

$$\mathrm{ss} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{E_i} \tag{24}$$

Safety stock and demand during the lead time are typically added to calculate reorder points. When current inventory levels fall below the order point, order costs are incurred. Reorder points are calculated by summing demand and safety stock during the lead time. Thus, it is defined as follows:

$$s = \left[\left[\mathrm{DS}_1 + \mathrm{DS}_2 + \mathrm{DS}_p\right]^T \begin{bmatrix} L_{r_1} \\ L_{r_2} \\ \vdots \\ L_{r_n} \end{bmatrix}\right] + \sum_{i=1}^{n} E_i \tag{25}$$

3.5.2 Ordering Cost

An inventory ordering cost is assumed to be fixed and varies from supplier to supplier when a spare parts order is placed for an FMEA block. In order to simplify the multiplication process, we place the $\mathbf{A}_{\boldsymbol{p}}$ as $1 \times m$ row matrix, which can be presented as follows:

$$\mathrm{A_p} = \begin{bmatrix} \mathrm{a}_1 & \mathrm{a}_2 & \cdots & \mathrm{a_n} \end{bmatrix} \;, \quad \mathrm{p} = 1,2, \ldots \mathrm{P} \tag{26}$$

Taking the frequency of orders per set and the ordering cost into account, then the ordering cost per block can be calculated as follows:

$$O_C = \left[\frac{\left[(\mathrm{A}_1 * \mathrm{DS}_1) + (\mathrm{A}_2 * \mathrm{DS}_2) + (\mathrm{A}_n * \mathrm{DS}_p)\right]}{Q}\right] \tag{27}$$

3.5.3 Inventory cost optimisation

Adding the holding, ordering, and shortage costs over an inventory cycle gives the total inventory relevant cost per FMEA block. That is:

$$\mathrm{Inv_b(Q)} = \mathrm{h} \,.\, [\mathrm{Q} + \textstyle\sum_{i=1}^{n} \mathrm{E_i}\,] + \left[\frac{[\,(A_1 * DS_1\,)+(A_2 * DS_2\,)+(A_n * DS_p)]}{Q}\right] + \mathrm{z}\,.\left[\frac{\left[[DS_1+DS_2+DS_p]^T \begin{bmatrix} L_{r_1} \\ L_{r_2} \\ \vdots \\ L_{r_n} \end{bmatrix}\right]}{Q}\right] \tag{28}$$

By setting $\frac{d\,\mathbf{Inv}\,(Q)}{dQ} = 0$, we can find Q^x's value. The economic order quantity is, therefore:

$$Q^x = \frac{\sqrt{[\,(A_1 * DS_1\,)+(A_2 * DS_2\,)+(A_n * DS_p)]+L_r * z}}{\sqrt{h}} \tag{29}$$

3.6 Optimisation Procedure

Due to the complexity of the proposed strategy, Genetic Algorithms (GAs) are used to find optimal solutions. This evolutionary optimisation technique was created by [30]. With this method, inventory management and maintenance strategy problems have been successfully optimised. For each decision parameter, the total cost of the FMEA block is calculated. The procedures used by GA for preventive maintenance scheduling and spare part inventory are shown in Figure 2.

With GA, global optima are found instead of local minima, as is often the case with gradient-based methods. In this method, a fixed population evolves based on the fitness value of the function in every iteration. We use crossover and mutation operators to evolve the population in the present problem. The fitness of the function is determined by total cost minimisation. The optimisation problem has been solved using MATLAB's function ga (). The decision variables have also been defined. The replacement strategy parameters t, $\mathbf{PC}$, PN, R_{time}, $\mathbf{S}$, $\mathbf{LC}$, $\mathbf{DTC}$, $\mathbf{SH}$ and inventory parameters $\mathbf{A_p}$, L, L_r, z, h are included as input parameters for every FMEA Block. Furthermore, each component's Weibull distribution parameters η and β. Q^x and T^x are the optimal variables for the problem.

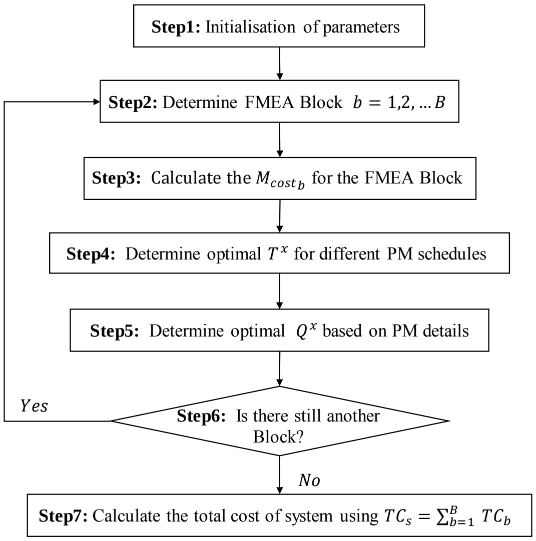

Figure 2. PM Scheduling and Inventory Strategy Procedure.

The problem has two cost components. Firstly, the first part of the cost is minimised with respect to T^x. The second part of the cost is minimised with respect to Q^x. The total cost of the FMEA block TC_b is then calculated based on the two cost components:

$$\mathrm{TC_b} = \sum_{b=1}^{B} \left(\frac{M_{cost_b}(T\,)+Inv_b(Q)}{R}\right) \tag{30}$$

Based on the sum of the FMEA blocks TC_b, the total cost of the whole system TC_s is calculated as follows:

(31)

4. Model Validation

A real case of Computer Numerical Control (CNC) system is examined in this study to illustrate the proposed method. The primary goal of this case study is to determine how active preventive maintenance strategy and inventory management based on FMEA could be used to maintain the continuity of system outcomes during maintenance activities. The system consists of two machines. Each machine contains a set of subsystems and components that are linked in series arrangements. The entire CNC system operates in parallel. In order for the system to function properly, all parts must be running. However, if one of the system's components fails, the entire system will not be affected.

4.1 CNC System Data

This optimisation model is analysed and applied to a CNC system based on the data set shown in Table 1. Based on historical failures and maintenance replacements of components, reliability characteristics (characteristic life η and slope β) were determined. It is also necessary to identify and incorporate into the FMEA model all factors influencing the reliability performance of the item during this step.

Table 1. Reliability Parameters and Components Cost.

Components	**Characteristic Life**	**Slope**	**Components Price**
Main Converter	3829	2.91	$1,900
Air Preparation Unit	2690	2.9	$1,100
Motor (electrical)	2200	3.51	$1,821
Grinder	2295	3.19	$1,119
Chuck (Actuation)	3377	3.14	$1,089
Pneumatic	2551	2.99	$1,208
Main Console	2982	3.66	$909
Pressure Tank	2516	2.96	$1,325
Air Preparation Unit VM	2101	3.25	$1,467
Motor (electrical) VM	2340	3.37	$1,782
Grinder VM	2198	3.42	$1,025
Directional Control valve	1534	3.6	$1,803
Gripper (Actuation)	1711	3.75	$1,270
Main Console VM	2767	3.73	$985

As well as failure characteristics, the historical data was used to estimate costs associated with preventive replacement operations and unexpected failures (in AUD). Components and labour are included in maintenance costs. Maintenance workers are assumed to be available at the time of planned maintenance. Assuming labour costs is $500, the preventive maintenance activity requires three people working for one hour each. Generally, sudden failures are more expensive than preventive maintenance. To perform the corrective maintenance, then the labour costs are assumed to be $500 (5 workers - 5 hours each - 25 hours total). Every time the block is unavailable due to a breakdown, the lost production cost is estimated at $900.

For inventory related costs, there are different costs associated with regular ordering from one supplier to another $\mathbf{A_1} = \$1000$, $\mathbf{A_2} = \$800$ and $\mathbf{A_3} = \$500$. In each FMEA block, we have three suppliers with constant lead times $L = 800\ h$. Costs associated with inventory holding $h = \$200$ and shortages $z = \$1000$ are fixed for each FMEA block.

5. Discussion and Results

5.1 Modeling of the CNC System

The CNC system was modeled using Maintenance Aware Design Environment (MADe) software [31]. It is an engineering software tool that identifies and evaluates potential safety and functional problems in a system by modeling components, subsystems, parts, and systems. From conceptualization to technological upgrades, the software can be applied to all forms of complex systems. Using this software, it is thus possible to simulate multiple simultaneous failure injections in the CNC system, which is useful for safety analysis.

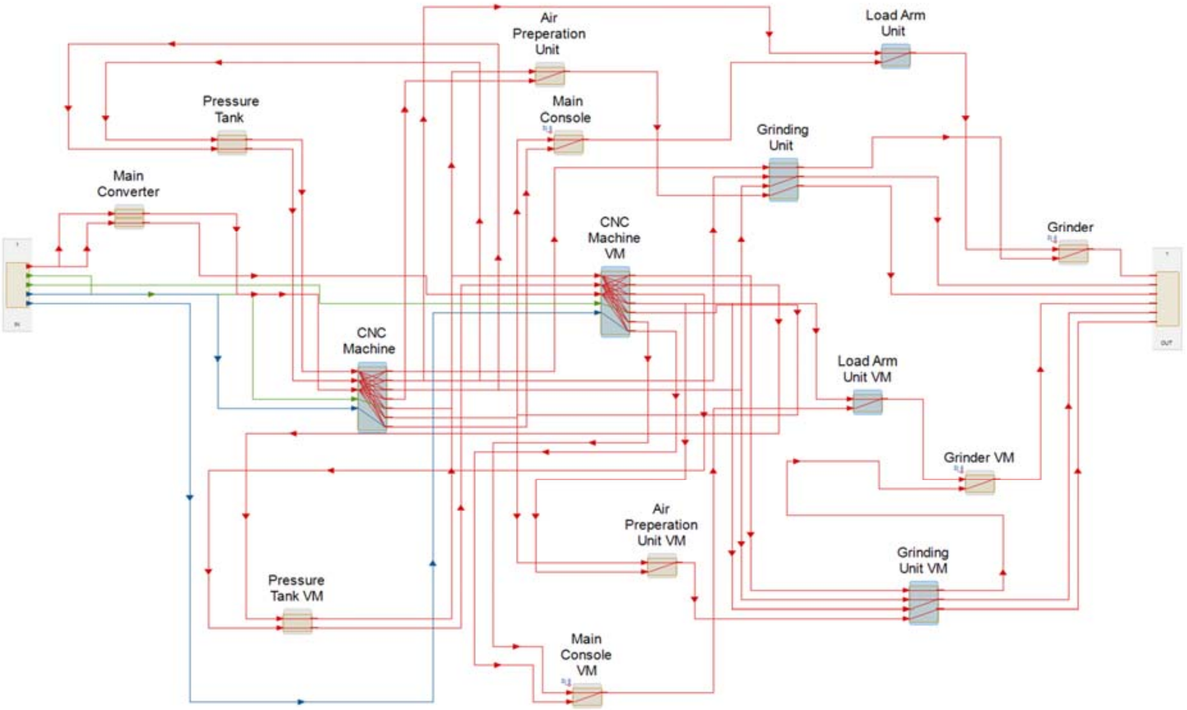

Figure 3. CNC System FMEA Model Captured in MADe

In order to investigate the propagation of failures, MADe creates a detailed functional model of the system. Functions and flows are analysed in a functional model in order to determine the impact of a functional failure. In this case, the components of the system are modeled, and the functional connections between them are represented by lines between the components. Modeling failure consequences and detecting causal relationships, each component's functions are analysed, as well as its connections to other elements. This enables the identification and documentation of potential failure modes. The functional link between a system component is represented by red, green, and blue connections, as shown in Figure 3.

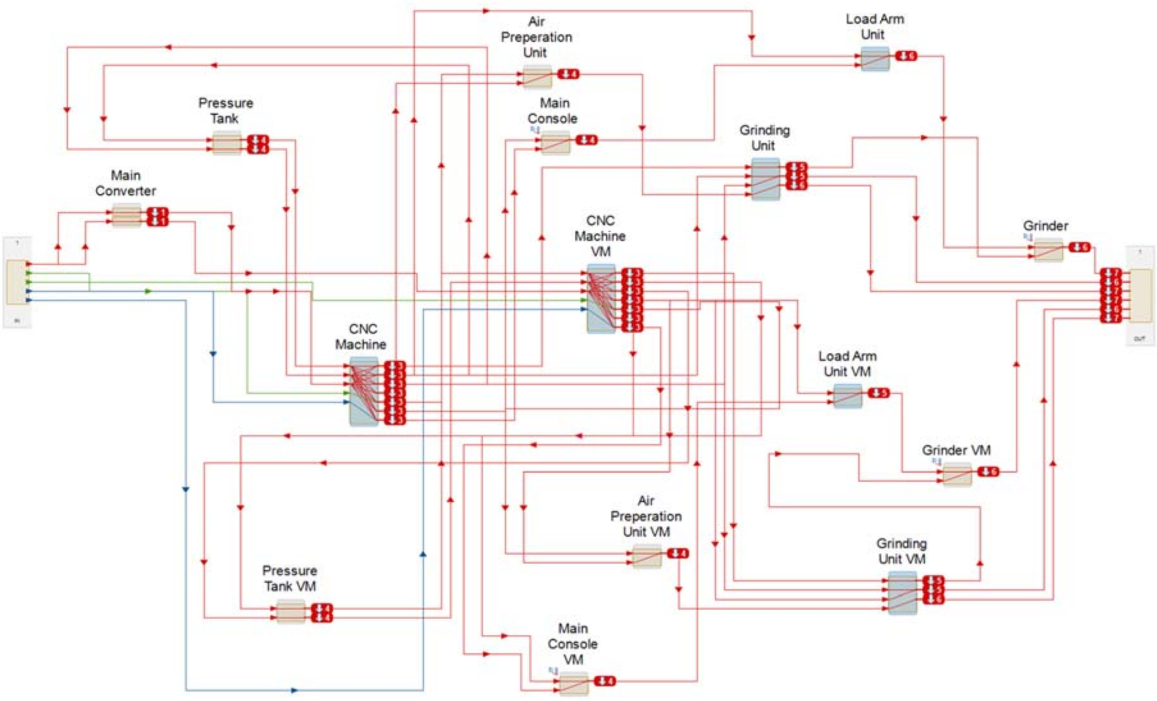

Figure 4. CNC System FMEA Model Simulated with Complete Faults Captured in MADe

5.2 Determining Failure Modes

After the CNC system is modeled in MADe, each component's function and the failure mode are specified using a functional diagram. When failure analysis is performed on the modeled system, a propagation analysis is performed on each component, and a transient response is assessed to potential failures that could occur. Whether a partial or complete failure occurs, failure propagation shows the number of components affected.

Complete failure propagation is simulated to examine how failures affect the CNC system. Analysing the simulation outcomes demonstrates how the system responds to failures and the level of system performance. The response of the system under critical situations can be determined by analysing multiple failures simultaneously. Steps are generated for each effect caused by the injected failures. The resulting steps explain all the components that have been affected. Using functional properties defined in the developed system model, thus failure injection is performed at the component level. Failure injection shows how a component responds to various failure scenarios, which can cause it to stop working. For example, if the Main Converter component is injected with low responses, the entire CNC system can be affected by failure see Figure 4. Through the FMEA model, however, we can see that the outcomes of the main component can power the two CNC machines. In other words, if one line is stopped, the other may continue to run. Therefore, from the FMEA model, we identify components that fail together as blocks based on their failure modes and effects. Consequently, this provides a sufficient understanding of how this system works and how it will fail. FMEA blocks in the following section describe how failures of a component affect other components.

5.3 Identification of Frist FMEA Block Spare Parts

The purpose of this section is to evaluate how failure modes can impact CNC system by simulating partial failure propagation. If one component fails in FMEA block 1, the CNC machine's entire line will stop. Every component within block one works in series with each other. Therefore, if only one component must be replaced and the block restarted, it is not practical to shut down the entire block. A preventive replacement is performed here for a group of components. Maintenance, in this case, will not affect the CNC machine VM during the replacement time. In other words, the CNC machine VM will continue to function when maintenance starts on block 1.

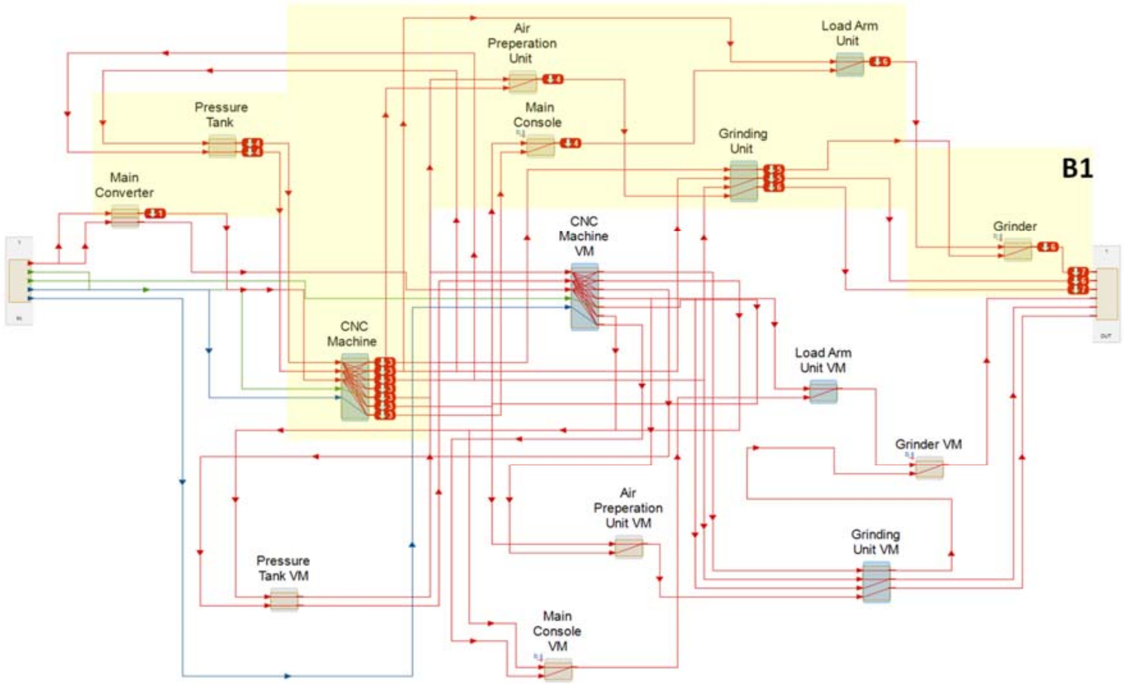

Figure 5. CNC System FMEA Model Simulated with Partial Faults of B1 Captured in MADe

Based on the FMEA model, it's apparent that only B1 (highlighted in yellow) is negatively affected by the failure of one line of the Main Converter. Figure 5 shows the fault sequence that occurs in the simulation model as it runs, showing where the fault originated and ended. In this way, the CNC system can continue working without being shut down for preventive maintenance since some working components are still present.

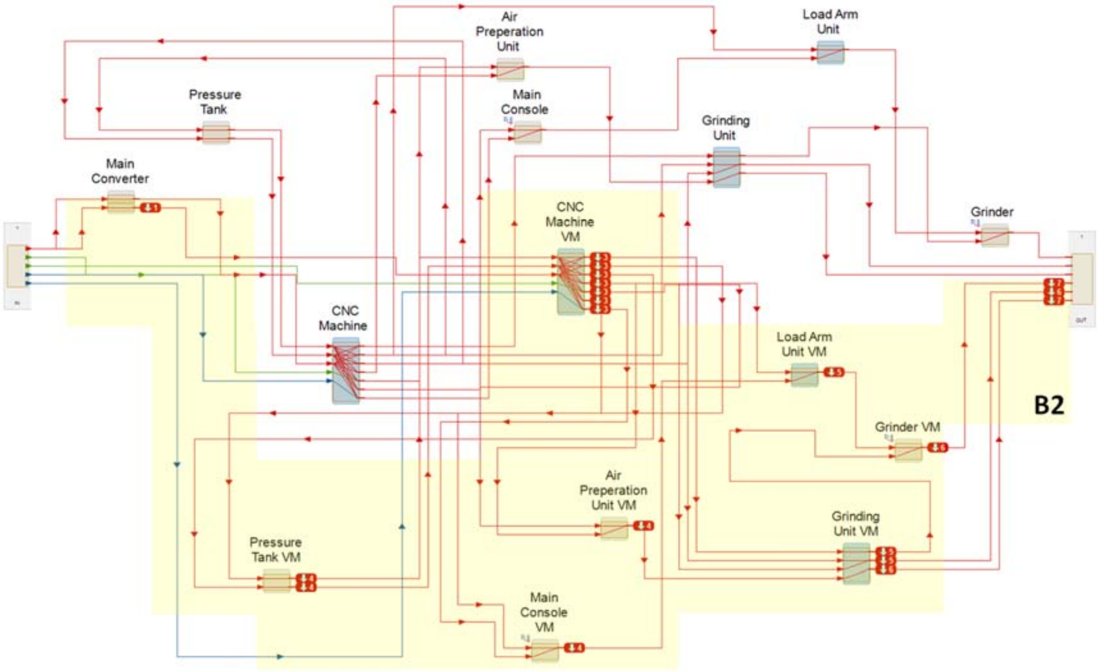

Figure 6. CNC System FMEA Model Simulated with Partial Faults of B2 Captured in MADe

The combination of FMEA and spare parts can assist in understanding the operation and failure behavior of the CNC system, therefore, identifying the spare parts required for each FMEA block. In this way, spare parts are ordered in a timely manner, ensuring that these parts are available for the block when maintenance is requested. This will prevent delays or unexpected failures.

5.4 Identification of Second FMEA Block Spare Parts

Since all components in block two are connected in series, failure of any part will shut down the entire block see Figure 6. There will be no impact on all components of the CNC system if the second line of the Main Converter fails. Only block two components will be affected by this failure. In other words, the failure will have only a partial effect on the whole system, as it won't stop working completely.

5.5 Optimal PM Schedule and Spare Parts Quantity

As a result of the analysis we conducted in the current section, the optimal values were determined for our model. MATLAB software was used to implement the model and verify the efficiency of the optimisation process. Once the optimal preventive replacement T^x has been determined, the quantity variable Q is optimised. The reorder levels s in each FMEA block are determined using actual demand over lead time plus optimised safety stock values.

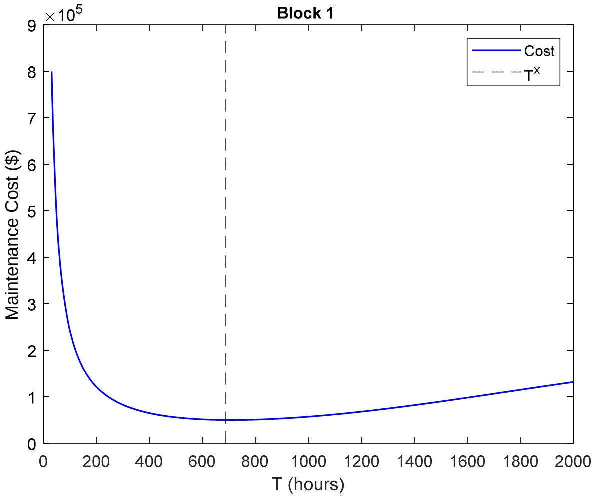

Figure 7. Expected Cost of Preventive Replacement Interval T for Block 1

MATLAB software was used to implement the proposed model, which can be used to compute the total maintenance cost by provisioning a spare part quantity. With Equation (15), the optimal preventive replacement interval is determined by minimising the overall replacement cost per unit of time. Figure 7 describes how replacement intervals have changed over time for block 1. As time increases, the rate of cost decreases until it reaches its minimum at = 687 h, after which it increases again. During the 2000 hours period, the block is replaced every 687 hours, which equals twice a year for this group of components.

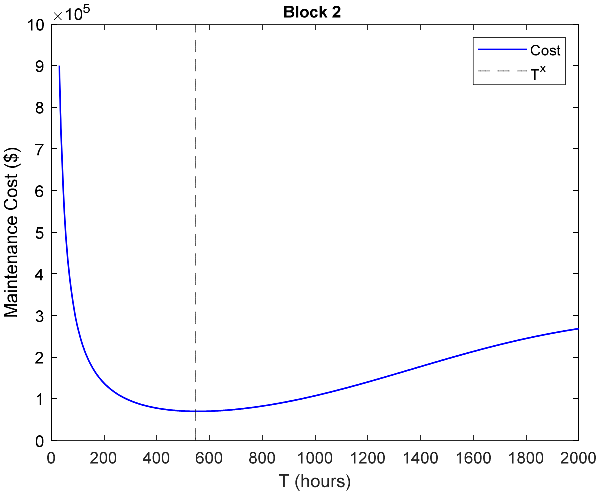

Figure 8. Expected Cost of Preventive Replacement Interval T for Block 2

While the components in the second block are replaced every 547 hours during the given period of time, thus the second block components are replaced three times a year. In Figure 8, we can see how increasing the time affects the expected cost per unit time. In this example, time increases, which results in the expected cost being reduced first reaching the optimal value and then increasing.

As can be seen in Table 2, the results of the optimisation process for all CNC system blocks are presented. Based on the replacement interval to replace spare parts, the optimal spare parts order quantity Q^x, and the total spare parts demand $\mathbf{D}_{\mathrm{B}_b}$ for each FMEA block are determined.

Table 2. The Result of Optimal Solutions for all System Blocks.

Blocks	T^x	Q^x	$\mathbf{D}_{\mathrm{B}_b}$	ss	TC_b
B1	687	47	16	8	$39.67
B2	547	38	27	9	$45.12

According to the optimal maintenance interval of 547 hours, the optimal quantity of spare parts for B2 is 47 for a year, with the estimated demand for spare parts being 27 and the total cost per block being $45.12. Based on the previous calculations for two blocks, the total cost TC_s of the CNC system using Equation (31) is $84.79 per year.

5.6 Complete CNC System Maintenance

In order to identify the components that work together and then identify failure modes, it is necessary to analyse the complete CNC system in depth. This is because it is necessary to know how it performs. With the combination of FMEA and inventory in terms of identifying the spare parts that are related to one another and understanding their behavior in terms of failure, preventive maintenance can then be easily scheduled, which helps in effective inventory management. Therefore, the whole CNC system does not need to be shut down, as only certain FMEA block components need to be replaced. It is possible, in this manner, to reduce the maintenance costs and the cost of spare parts of the system.

As we discussed in the previous section, blocks have functionally related components, i.e., if one fails, they will all fail. Block one, for example, should be replaced in 687 hours. These components have been replaced twice a year based on the 2000 h (one year) period. The expected components demand during this period can be calculated once the number of preventive replacements is determined. Whenever there are more replacements, more demand is expected.

The remaining components of the CNC system have not been replaced, for instance, those in B2 when we replaced B1. Fig. 9 illustrates that preventive replacement intervals are different for each block. In other words, they do not coincide with one another. Consequently, they may continue operating during maintenance activities, which ensures continuous operation, even if partial, and eliminates the requirement to order additional spare parts.

All components in each FMEA block have been divided into three groups according to spare part suppliers. Each group has a different supplier and a different order cost. The ordering process from the same supplier may require too many repetitions if only one part has been replaced without considering failure modes. Thus, increasing the cost in the total cost. Additionally, the cost may increase if we replace one component of each block at the same time. In this case, the entire CNC system will be shut down, which will result in a stoppage of the system's outputs. Our approach in this study is, therefore, useful. The FMEA block is used to replace the components as part of the maintenance process. Moreover, the reliability of the block can be maintained at an acceptable level by replacing the components at the specified optimum time.

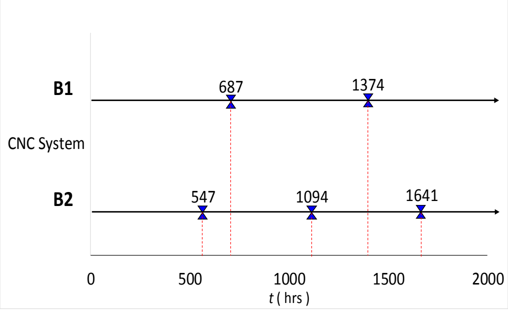

Figure 9. The Maintenance Schedule of the Complete System

By understanding the failure modes of the entire CNC system and optimising each model, the total cost of maintenance and spare parts management is integrated. Therefore, under our failure modes-based approach, we are able to guarantee half of the system output capacity during maintenance times with spare parts available on any given FMEA block.

6. Conclusion

In this paper, an integrated FMEA and inventory preventive maintenance scheduling methodology with detail consideration of failure modes is presented for ensuring the continuity of complex CNC system outcomes during preventive maintenance activities. This research has the following main contributions to develop this integrated methodology:

1. Realisation of the FMEA block model concept to schedule preventive maintenance such that continuity of production is assured.
2. Complete mathematical formulation based on Weibull distribution and economic stock control theory using FMEA block replacement concept has been developed.
3. The mathematical formulation in this paper is able to adjust spare parts ordering strategy according to performance of suppliers.

With these fundamental theoretical developments, the optimal intervals for preventive maintenance and spare parts quantity can be specified for each block of the FMEA. Modelling subsystems and components using FMEA in series and parallel has been done. The FMEA block is determined after identifying the failure modes of CNC system components and subsystems.

For each FMEA block, the probability distribution of component failures could be integrated with the scheduling requirements. By considering both preventive and corrective maintenance costs for each FMEA block, the algorithm determined the optimal intervals for preventive maintenance and its required inventory of spare parts.

The methodology is illustrated by a case study of the CNC system involving multi-nonidentical components to demonstrate the effectiveness of our approach. The results illustrate the importance of understanding the system behaviour with detailed consideration of failure modes in order to ensure the continuity of the system, even partially during preventive maintenance activities.

For future studies, some assumptions can be relaxed. The lead time for each spare is constant. However, spare parts commonly have different lead times in practice. Spare parts ordering with a long lead time can be considered.

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