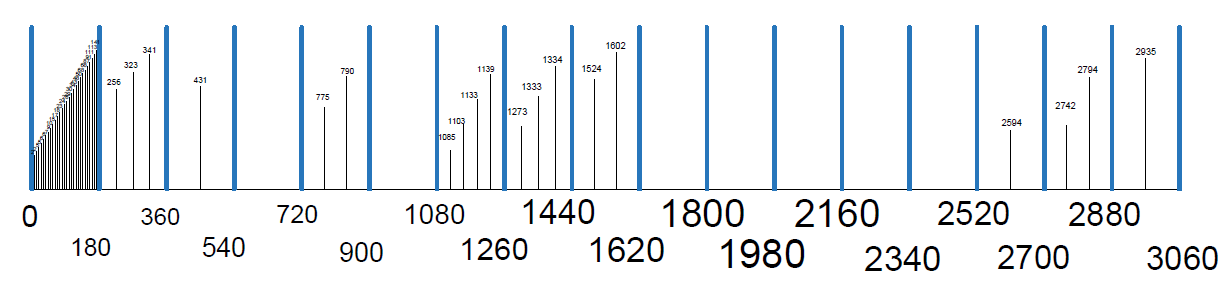
**3. RCBM Strategy**

The methodology for the application of RCBM strategy consists of formulation of a better and efficient ‘Maintenance Policy’ based on Reliability analysis of components from maintenance records and evaluation of a ‘Cost Model’ (described in subsequent sub-sections), in order to achieve economical and effective maintenance. This is followed by optimization of maintenance schedules for each component, in order to minimize the overall cost of maintenance.

The aforementioned methodology incorporates following assumptions:

1. If a component is replaced during regular maintenance or unexpected failures, the reliability of the component will be restored to 100% after replacement.
2. The time window for optimized cost calculation and applied maintenance strategy is based on the existing maintenance period (3060 days) for fair comparison.
3. The failure mechanism of one component does not interact or influence the same for another to maintain simplicity.

***3.1 Reliability Based ‘Maintenance Policy’***

In order to design a new maintenance policy, the maintenance records from the hospital, for a duration of about 8 years is studied. The current maintenance policy revolves around cyclic maintenance of 180 days wherein faults are diagnosed during regular maintenance or unexpected failures, and rectified by replacing the faulty component. Figure 3 shows the stick-diagram for the existing maintenance strategy of a component presented as a Network Terminal Box (NTB) for illustration. The blue dotted sticks represent 180-day regular maintenance and the black-small sticks represent the actual failures that happened in-between regular maintenance cycles.

*Figure 3. Stick-diagram for the existing maintenance strategy of a component presented as Network Terminal Box, for illustration.*

Figure 3 highlights two major issues associated with the existing maintenance strategy. *Firstly*, the initial failures (within the first 180 days) are large in number which was not detected earlier before our analysis, and *secondly*, unexpected failures occur quite often, in-between regular maintenance period. All these lower the operational availability of the equipment, and increases the incurred cost due to unexpected maintenance and the need of spare machines in order to maintain high availability. The first issue can be detected through standard data logging. However, the second issue requires the study of the reliability of each component.

In order to improve the existing maintenance strategy, the maintenance record for each of the 19 components mentioned in Table I, comprising the Haemodialysis machine is analysed using Weibull++ v10 by Reliasoft. The failure times and reliability of each component (excluding initial failures) are estimated using the Cumulative Distribution Function (CDF) based on specific statistical distribution associated with the specific components as shown in Table II. Assuming the reliability of each component must be above 0.97, which implies that the chance of the failure of each component is only 0.03, we can derive a suitable maintenance cycle for each component as shown in Table III.

*Table II. 220-Day Maintenance Scheduling based on Reliability Data. (without considering the initial failures)*

|  |  |  |  |
| --- | --- | --- | --- |
| **S. No** | **Component** | **Associated Statistical Distribution** | **Distribution Parameters** |
| 1 | M29 | 2P-Weibull | Beta: 2.49, Eta (Day): 971.02 |
| 2 | V39 | 3P-Weibull | Beta: 1.32, Eta (Day): 5345.53, Gamma (Day): 89.06 |
| 3 | RV | 2P-Weibull | Beta: 2.30, Eta (Day): 2612.57 |
| 4 | TMP | 2P-Weibull | Beta: 2.10, Eta (Day): 3736.00 |
| 5 | NTB | 2P-Weibull | Beta: 2.08, Eta (Day): 2743.23 |
| 6 | BLD | 3P-Weibull | Beta: 0.74, Eta (Day): 4050.97, Gamma (Day): 196.61 |
| 7 | G29 | Lognormal | Log-Mean (Day): 7.34, Log-Std: 0.70 |
| 8 | F210 | Gamma | Mu (Day): 7.77, K: 1.78 |
| 9 | M21 | 3P-Weibull | Beta: 1.93, Eta (Day): 1833.00, Gamma (Day): 4.19 |
| 10 | RCh | 2P-Weibull | Beta: 1.55, Eta (Day): 9503.80 |
| 11 | CCB | 3P-Weibull | Beta: 0.89, Eta (Day): 21327.93, Gamma (Day): 351.63 |
| 12 | ST | Lognormal | Log-Mean (Day): 7.99, Log-Std: 0.15 |
| 13 | AKOR | Lognormal | Log-Mean (Day): 8.46, Log-Std: 0.76 |
| 14 | 65R | 3P-Weibull | Beta: 2.24, Eta (Day): 3711.45, Gamma (Day): 375.00 |
| 15 | FC | Gamma | Mu (Day): 8.24, Gamma (Day): 1.82 |
| 16 | PS | 2P-Weibull | Beta: 2.08, Eta (Day): 3579.83 |
| 17 | CP | 2P-Weibull | Beta: 1.47, Eta (Day): 12556.33 |
| 18 | HP | Lognormal | Log-Mean (Day): 8.70, Log-Std: 0.70 |
| 19 | AKT | Lognormal | Log-Mean (Day): 7.96, Log-Std: 0.37 |

*Table III. 220-Day Maintenance Scheduling based on Reliability Data.*

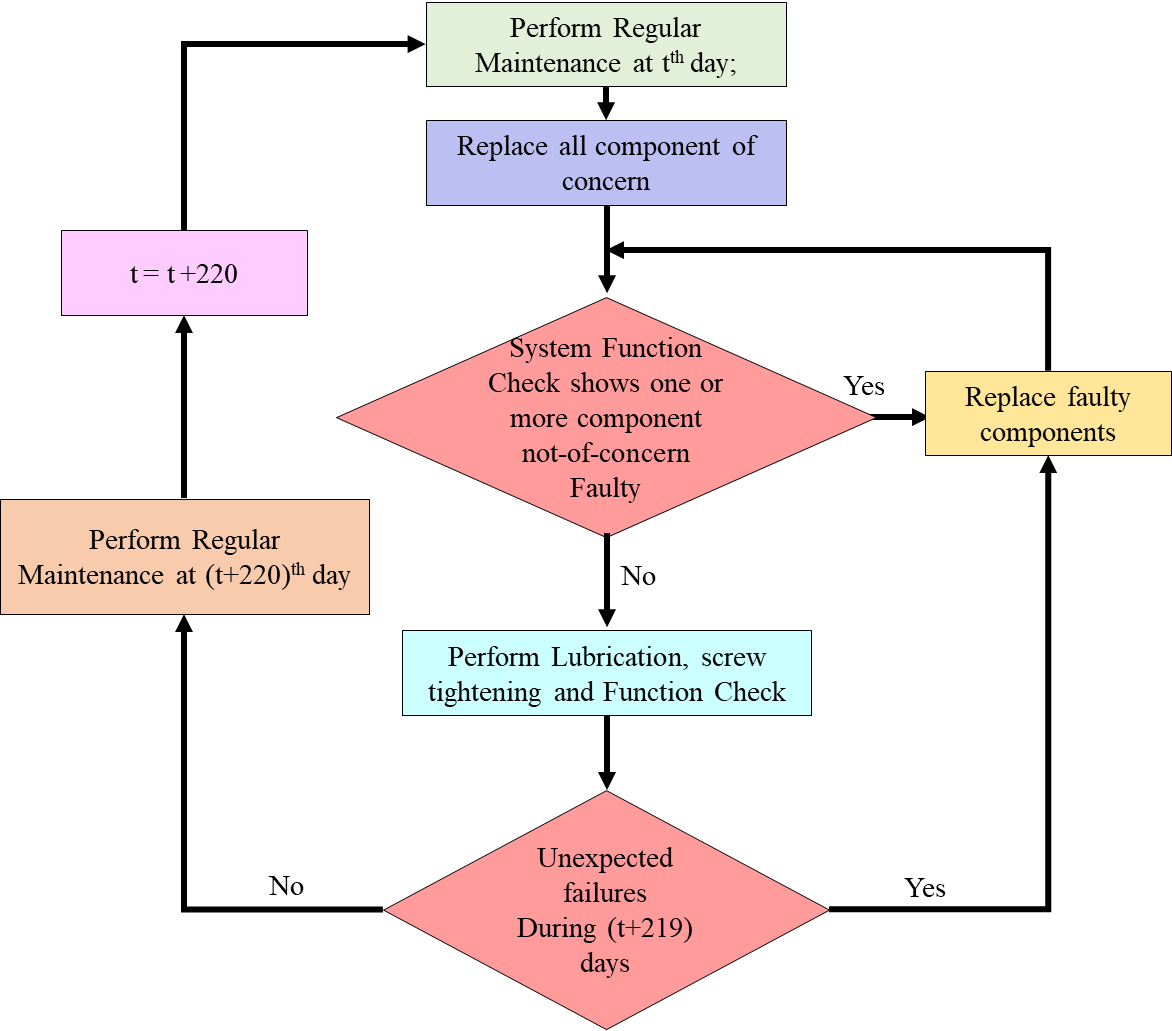
|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Maintenance Cycle | Components of-concern to be maintained in | | | Total No. of Components to be maintained |
| ***220 days*** | ***440 days*** | ***1100 days*** |
| *1st cycle on 220th day* | M29, V39, RV, TMP, NTB, BLD, G29, F210, M21, RCh | - | - | 10 |
| *2nd cycle on 440th day* | M29, V39, RV, TMP, NTB, BLD, G29, F210, M21, RCh | CCB, ST, AKOR, 65R, FC, PS, CP | - | 17 |
| *3rd cycle on 660th day* | M29, V39, RV, TMP, NTB, BLD, G29, F210, M21, RCh | - | - | 10 |
| *4th cycle on 880th day* | M29, V39, RV, TMP, NTB, BLD, G29, F210, M21, RCh | CCB, ST, AKOR, 65R, FC, PS, CP | - | 17 |
| *5th cycle on 1100th day* | M29, V39, RV, TMP, NTB, BLD, G29, F210, M21, RCh | - | HP, AKT | 12 |
| *6th cycle on 1320th day* | M29, V39, RV, TMP, NTB, BLD, G29, F210, M21, RCh | CCB, ST, AKOR, 65R, FC, PS, CP | - | 17 |
| *7th cycle on 1540th day* | M29, V39, RV, TMP, NTB, BLD, G29, F210, M21, RCh | - | - | 10 |
| *8th cycle on 1760th day* | M29, V39, RV, TMP, NTB, BLD, G29, F210, M21, RCh | CCB, ST, AKOR, 65R, FC, PS, CP | - | 17 |
| *9th cycle on 1980th day* | M29, V39, RV, TMP, NTB, BLD, G29, F210, M21, RCh | - | - | 10 |
| *10th cycle on 2200th day* | M29, V39, RV, TMP, NTB, BLD, G29, F210, M21, RCh | CCB, ST, AKOR, 65R, FC, PS, CP | HP, AKT | 19 |
| *11th cycle on 2420th day* | M29, V39, RV, TMP, NTB, BLD, G29, F210, M21, RCh | - | - | 10 |
| *12th cycle on 2640th day* | M29, V39, RV, TMP, NTB, BLD, G29, F210, M21, RCh | CCB, ST, AKOR, 65R, FC, PS, CP | - | 17 |
| *13th cycle on 2860th day* | M29, V39, RV, TMP, NTB, BLD, G29, F210, M21, RCh | - | - | 10 |
| *14th cycle on 3080th day* | M21, RCh | - | - | 2 |

From our reliability analysis of the components, we found that their reliabilities are adequately high, apart from their early failure, and thus 180-days maintenance cycle is too conservative. Also, Table III shows that not all the 19 components need to be maintained during the regular maintenance. In a given period of 3060 days, 10 components including M29, V39, RV, TMP, NTB, BLD, G29, F210, M21, RCh are to be maintained every 220 days, 7 components including CCB, ST, AKOR, 65R, FC, PS, CP are to be maintained every 440 days, 2 components including HP, AKT are to be maintained every 1100 days. The 14th cycle has an exception of only 2 components (M21 and RCh) instead of 10 in 220 day cycle. Figure 4 shows the suggested 220-day maintenance strategy.

On comparing the current 180-days maintenance policy with the suggested 220-days maintenance policy, one can obtain the following major advantages:

* + Number of maintenance cycles reduce to 14 cycles from 17 in a given period of 3060 days.
  + The regular maintenance cost reduces by 18.18%.
  + This results in a total saving of 18,279 New Taiwan Dollar (NTD) per year per machine (excluding initial and unexpected failures’ consideration)

The initial failures are not included in the cost saving calculations because those can be avoided by considering better quality components or by considering a different vendor. In order to study the cost saving including the unexpected failures, a Cost-Model is presented in the next sub-section

****

*Figure 4. Suggested 220-day maintenance policy*

***The Cost Model***

The ‘Cost Model’ is formulated in order to evaluate the cost-saving from the suggested maintenance strategy including both expected and unexpected failures as well as for optimization of maintenance strategy. Assuming there are k components and the replacement period of component *i* to be *ti*, then the total cost of maintenance can be given by equation (1).

(1)

where, *Cex,i* and *Cuex,i* are the total costs of maintenance for the component *i* over all its expected replacements (i.e. planned replacement) and all the unexpected replacements (due to unexpected failures) respectively, *Ctk* is the cost of regular maintenance and *Crp* is the recursive cost of functional check and rinse that is counted repeatedly in the equation (1) when more than one component is repaired in an event of multiple failures. This cost model includes the probability of failures’ for every component at a particular time. The detailed calculation of each term will be discussed later.

With this equation, we can employ RCBM policy to minimize the total cost of maintenance as follows, where *Cm* is the minimum total cost of maintenance.

(2)

The detailed calculations of the 4 terms in equation (1) are deduced below:

*3.2.1 Expected cost of Replacement (*

As replacement of components are bound to happen, the expected cost of replacement ( ) for k components is the summation of expected cost of replacement for *ith* component which can be computed as the sum of the price of the component *Pi* and the manpower cost as given below.

(3)

where and are the man-hour for replacing and performing function check-rinse respectively, and is the manpower cost per hour.

Hence, the expected cost of replacement for k components is given by equation (4).

(4)

where represents the expected number of replacements within a specific time interval of *Ts*.

*3.2.2 Regular maintenance cost*

The regular maintenance involves basic function check-rinse and repairing using a tool kit which costs. Thus, the regular maintenance cost is given by equation (5).

(5)

where is the regular maintenance period, is the time of repairing work and function check and rinse (about 2 hours) and is the manpower cost per hour.

*3.2.3 Unexpected cost of Replacement (*

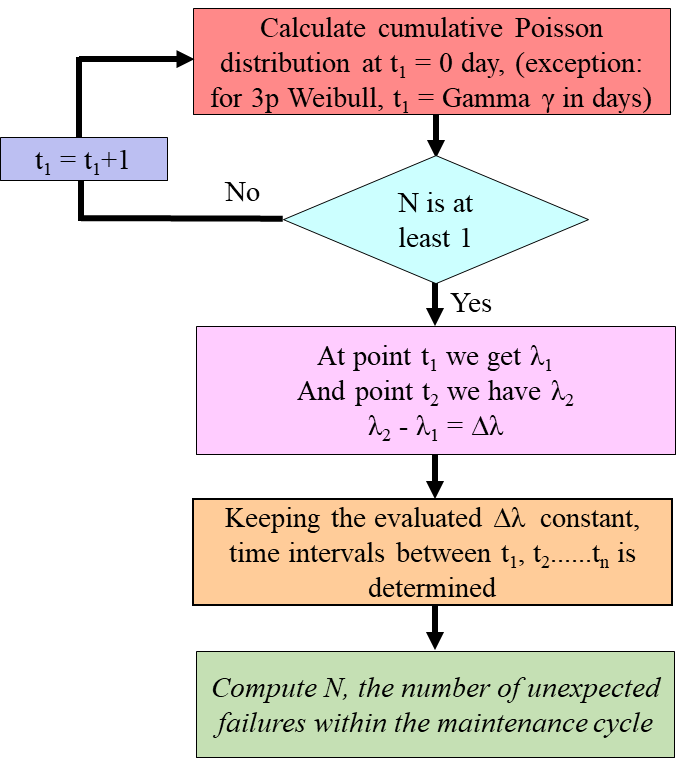
Unexpected failure can happen in-between designated maintenance cycles. In order to calculate the unexpected cost of replacement, number of unexpected failures is to be determined using the Non-Homogeneous Poisson’s (NHP) process [26]–[28], as the failure rate of all the components are time-dependent.

To apply NHP process, one need to determine the time interval so that the failure rate can be treated as a constant within the interval. However, too large the time interval will produce error as the variation in the failure rate will be too high to be considered as approximately constant. Too small the interval will also produce error as the number of failure will be zero.

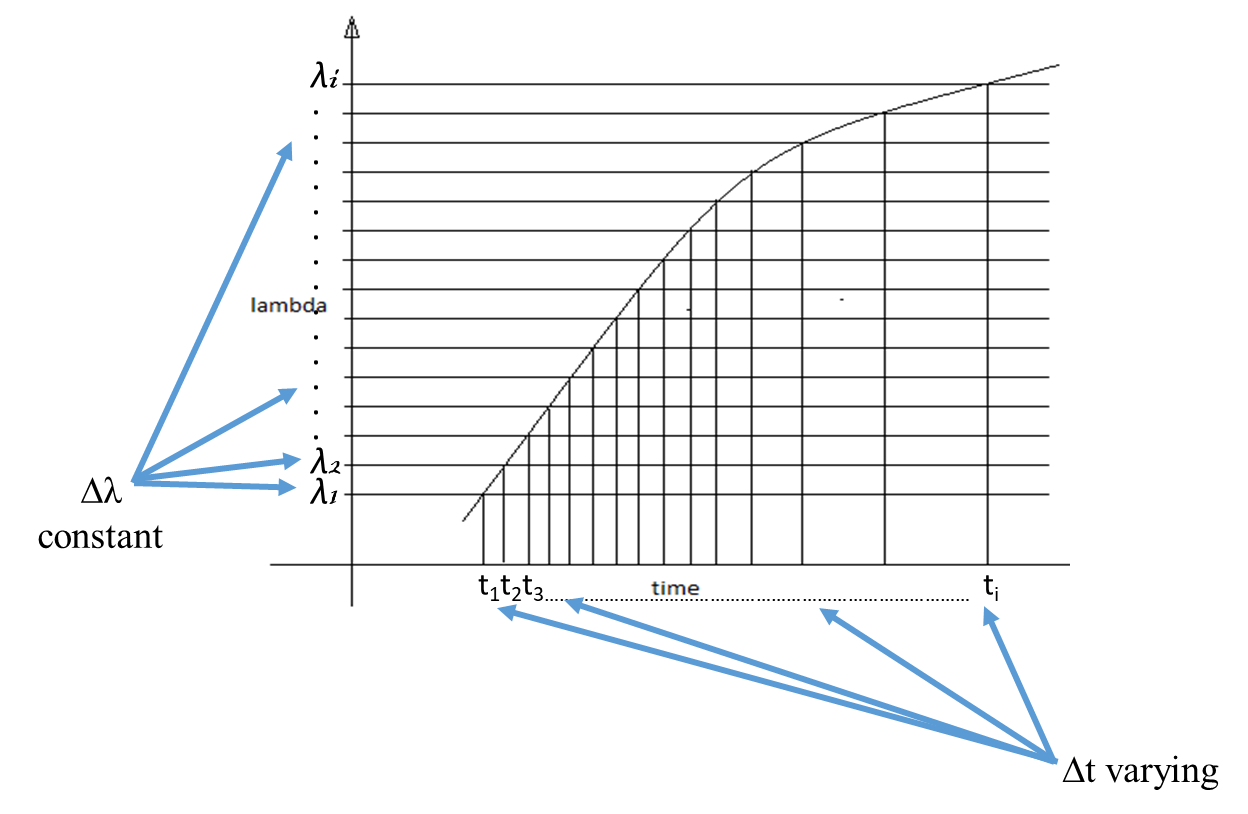
Therefore, the interval is determined as shown in Figure 5 where the time interval is first obtained such that it is not too small to have zero failure and yet not too big for large failure rate variation.

Figure 6 shows an example of the failure rate vs time curve as derived from the reliability function of a component given as [29]

where *F(t)* is the cumulative density function given as *F(t)=1-R(t)*.



*Figure 5. Procedure to calculate number of unexpected failures.*



*Figure 6. ‘Plot-Division’ to determine ∆t based on constant ∆λ.*

In Figure 6, the failure curve is divided into time intervals in such a way that the *∆t* will be varied according to the curve while *∆λ* will be constant. Table IV shows an example for the calculation of *N* in case of a component- Motor 29, for a time period of 25 days, which is its replacement period.

*Table IV. An example of calculation of N in case of a component- Motor 29, for a time period of 25 days*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **N** | **Time** | **lambda** | **Reliability** | **Poisson Distribution, PN** | **Cumulative Poisson Distribution** | **N\*PN** |
| 0 | 25 | 0.000619 | 0.984644123 | 0.993829119 | 0.9938291 | 0 |
| 1 | 25 | 0.000619 | 0.984644123 | 0.006151802 | 0.9999809 | 0.006151802 |
| 2 | 25 | 0.000619 | 0.984644123 | 1.90398E-05 | 1 | ~0 |
| 3 | 25 | 0.000619 | 0.984644123 | 3.92855E-08 | 1 | ~0 |

From Table IV, unexpected failure cost for Motor 29 for a time period of 25 days can be calculated as,

In general, the equation for Unexpected Cost calculation can be expressed as shown below.

(7)

where is the Expected value of the number of unexpected failures within for component *i*,

which is the remaining time before the ends and after the last replacement of component ,

and is the replacement cost of the *ith* component as shown in equation (3).

*3.2.4 Repetitive Cost of Function Check and Rinse*

During a repair event, if there are more than one components that have to be replaced or, if this repair event coincides with the regular maintenance event, the function check and rinse will only be performed once. In order to compensate the repetitive calculation of the cost of function check and rinse as evident from equations (3) and (5), the term is subtracted from the summation of total expected cost, unexpected cost and regular maintenance cost in equation (1). Assume there are repair event in an interval , repetitive cost of function check and rinse is given by equation (8).

(8)

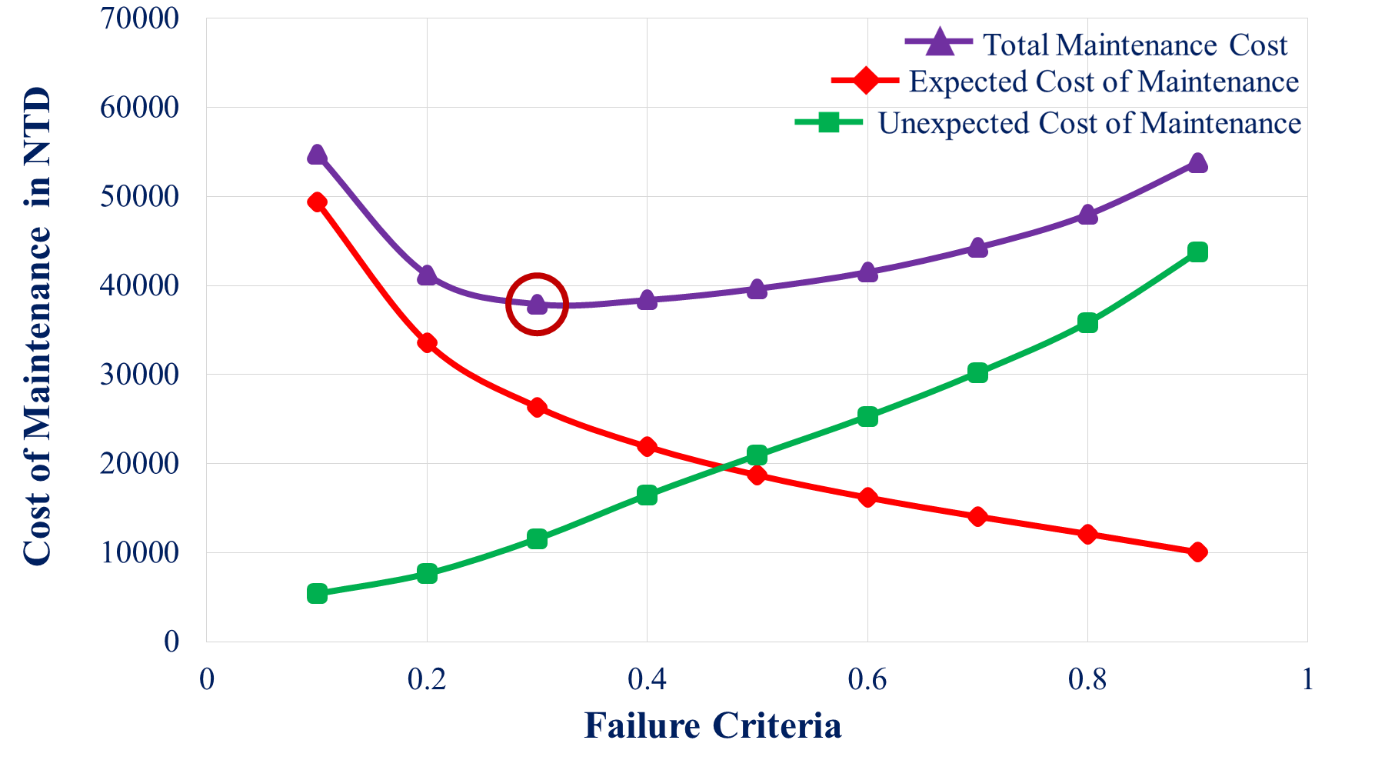
where is the number of the components (if component replacement coincides with the regular maintenance, tool kit is also considered as a component) that have to be repaired in the repair event

With such calculation, and the change of the regular maintenance period from 180-days to 220-days, and taking both the expected and unexpected failures into consideration, the 220-days maintenance period results in a reduction of the maintenance cost by 18.18%.

*3.2.5 Best Case Failure Criteria for Minimization of Total Maintenance Cost*

The Total Maintenance Cost calculation as shown above assuming the reliability of each components must be above 0.97 or failure criteria of 0.03. Such high reliability criteria can reduce the number of unexpected failures within a maintenance cycle, but it will shorten the maintenance period and thus increases the expected cost of maintenance. Figure 7 shows the plot of Total Maintenance Cost for one of the components- Motor 21 (M21) with respect to the varying failure criteria as computed using Equations (4)-(8).

From Figure 7, one can see that the minimum total maintenance cost occurs when the failure probability is chosen to be 0.3, neither too high nor too low. However, the plot in Figure 7 is specific to only one component. Every other component will have similar curve with different failure criteria for minimum value of Total Maintenance Cost resulting in different replacement periods. Therefore, there is a need for optimization of the maintenance periods in order to cater for different failure criteria and minimization of Total Maintenance Cost.

****

*Figure 7. Cost of Maintenance vs Failure Criteria chosen for replacement period and regular maintenance of Motor 21; red solid circle shows the point of lowest total cost of maintenance for Motor 21.*

**4. Optimization based on RCBM Policy**

In order to perform optimization, Genetic Algorithm [30], [31] is employed in this work owing to its evolutionary [32] and heuristic nature [33]. The basic principle of Genetic Algorithm (GA) is based on the biological evolution and natural genetics and selection concepts. Genetic Algorithm optimize given parameters by mutation, crossover and fitness selection to find the optimum results of the given problem. Since the number of components that have to be repaired in a repair event does not hold a linear relation with the periodic replacement of components, GA is suitable for such nonlinear optimization problem.

In this work, Genetic Algorithm function is implemented in MATLAB optimization toolbox using the ‘Cost Model’ derived in the previous section, so as to find the best periodic replacement for each component. The steps for implementation of GA is shown in the Appendix.

**5. Results and Discussions**

*5.1 Optimized Maintenance Schedules*

The Genetic Algorithm execution results in the optimized maintenance schedules is summarized in Table V.

*Table V. Optimised Maintenance Schedules deduced from GA*

|  |  |  |
| --- | --- | --- |
| **S. No** | **Component** | **Optimised Maintenance Schedule (in Days)** |
| 1 | M29 | 780 |
| 2 | V39 | 1950 |
| 3 | RV | 1830 |
| 4 | TMP | 1890 |
| 5 | NTB | 1860 |
| 6 | BLD | 3090 |
| 7 | G29 | 1860 |
| 8 | F210 | 2040 |
| 9 | M21 | 1830 |
| 10 | RCh | 1890 |
| 11 | CCB | 2880 |
| 12 | ST | 2340 |
| 13 | AKOR | 780 |
| 14 | 65R | 1890 |
| 15 | FC | 630 |
| 16 | PS | 1710 |
| 17 | CP | 630 |
| 18 | HP | 3090 |
| 19 | AKT | 780 |

The optimized maintenance periods shown in Table V correspond to minimized Total Maintenance Cost value of 359,102 NTD during 3060 days for a given machine. The suggested replacement period of components BLD and HP is 3090 days which is greater than 3060 days. This means that these components do not require any periodic replacement during 3060 days.

*5.2 Comparison of Average Cost of Maintenance*

The average cost of maintenance of one machine (ACoM) is calculated as follows.

(9)

where r is the number of machines, is the total cost of maintenance of machine ‘j’ and is the age of machine ‘j’ in days. All the machines are divided into four groups in order to draw a fair comparison between the actual maintenance cost and the corresponding optimized value as shown in Table VI.

*Table VI. Classification of Machines on the Basis of Age and Comparison of ACoM for 180-day maintenance policy and optimized RCBM policy.*

| ***Group*** | No. of Machines | Age (in days) | ACoM for (Unit/day) | |
| --- | --- | --- | --- | --- |
|  |  |  | 180-day Regular Maintenance | Optimized RCBM |
| *Group A* | 29 | 227 | 38.09 | 16.98 |
| *Group B* | 45 | 1642 | 169.51 | 63.66 |
| *Group C* | 4 | 1703 | 209.40 | 65.21 |
| *Group D* | 4 | 3024 | 250.07 | 117.16 |

Figure 8 shows the comparison of the ACoM for all the four groups associated with the conventional and optimized PdM strategy.

*Figure 8. Comparison of ACoM between the machine groups with existing 180-day policy and optimized RCBM strategy.*

Using the optimized RCBM strategy, huge cost saving is exhibited with respect to the ACoM as shown in Table VI and Figure 8. The Average Cost of Maintenance of a machine which follows the current 180-day regular maintenance strategy is 128.91 Unit$/day. This value decreases to 78.83 Unit$/day in case of Reliability based 220-day maintenance strategy. The ACoM for the optimized RCBM strategy further reduces to 49.84 Unit$/day, accounting for almost 60% of the total cost saving. The reasons for the resulting cost saving are due to reduction in the following:

* number of maintenance cycles,
* use of tool kit and manpower for the maintenance and,
* over-maintenance and under-maintenance schedules of specific components according to the evaluated reliability.

*5.3 Comparison of Operational Availability*

The operational availability (OpAv) [34], [35] for a given system is defined as the fraction of average availability over a period of time and is expressed by equation (10).

(10)

where MTBF is the Mean Time Between Failures and MDT is the Mean Down-time.

Table VII shows a comparison of MTBFs, MDTs and OpAVs of the current 180-day maintenance policy and optimized RCBM policy.

*Table VII. Comparison of Operational Availability for 180-day maintenance policy and optimized RCBM policy.*

|  |  |  |  |
| --- | --- | --- | --- |
| **Maintenance Policy** | **MTBF**  **(in days)** | **MDT**  **(in days)** | **OpAv** |
| 180-day Regular Maintenance | 622.02 | 3.0200 | 0.99517 |
| Optimized RCBM | 742.82 | 0.0384 | 0.99995 |

The operational availability (OpAv) calculated for the optimized RCBM is much higher than the same for 180-day regular maintenance practice.