CIGI QUALITA MOSIM 2023

Development of economical partial multi-component maintenance strategy taking into account reliability and environmental constraints

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***Abstract* – Maintenance is a vital aspect of industrial companies as it significantly impacts production quality, but it can also be complex to implement. Maintaining production equipment not only makes it more reliable but also increases its availability rate, resulting in financial gains for the company. Maintenance practices have continuously evolved since their inception after World War II, now reaching its fourth generation, known as Maintenance 4.0. This latest iteration utilizes advanced technologies from Industry 4.0 to enhance maintenance strategies, including multi-component maintenance strategy, a new approach based on self-prediction techniques to identify and correct faults.**

This paper aims to develop a partial multi-component maintenance strategy that considers economic, environmental, and reliability constraints. The model determines the optimal number of reserve components and the ideal timing for preventive maintenance actions, ultimately making this strategy more cost-effective than a single-component system. By using this model, companies can optimize their maintenance strategies to minimize costs while improving equipment reliability.

***Keywords* – preventive maintenance, maintenance strategies, single-component system strategy, multi-component maintenance strategy.**

1 INTRODUCTION

The emergence of Maintenance 4.0, in conjunction with Industry 4.0, seeks to promote collaboration between production planning and maintenance in order to achieve a profitable production system through efficient maintenance practices. According to Jasiulewicz et al., (2019), the role of maintenance is evolving to better support value creation by contributing to the economic, environmental, and social dimensions of a business.

Industry 4.0 has brought about new maintenance strategies, including self-maintenance. Silvestri et al., (2020) define self-maintenance as an approach based on the nine pillars of Industry 4.0, which considers the application of Maintenance 4.0 as the first step towards implementing Industry 4.0. Bona et al., (2021) notes that while Industry 4.0 originated in 2011, the first articles describing maintenance strategies based on new technologies were published from 2015 onwards, with the most recent ones in 2019. The concept of self-maintenance has been discussed in previous research, with Labib (2006) defining it as a machine's ability to self-monitor, diagnose, and repair itself to maximize uptime. Lee & Wang (2008) suggest that self-maintenance aims to add intelligence to a system so that it can detect and diagnose failures, and maintain equipment in the event of a breakdown. According to Morelloa et al., (2010), the benefits of self-maintenance include cost reduction, improved product quality, and minimizing or even eliminating downtime.

The design of a self-maintenance system, according to Echavarria et al., (2007), is based on embedded intelligence and sensors to detect faults, which adds robustness and fault tolerance. Burhanuddin et al., (2009) specify three functions of self-maintenance: monitoring the current state of the system, learning from previous repair activities, and redundancy.

In conclusion, self-maintenance can be applied to all industrial fields, but is particularly recommended by Lee et al., (2011) for equipment with high uncertainty and risk. It is a non-intrusive approach that offers more advanced solutions than preventive maintenance, while also being cost-effective.

2 PROBLEM DESCRIPTION

To move from a single-component system to a multi-component system, with a passive redundancy configuration three aspects must be taken into account: economic, reliability, and environmental. The goal is to determine the optimal number of components required in the system to ensure that the multi-component strategy is more cost-effective compared to the single-component strategy over a finite horizon H. This determination is achieved by evaluating the total cost, which integrates the initial acquisition cost, the maintenance costs, and the cost of recycling failed components over the horizon H. The multi-component maintenance strategy's costs are compared with those of the single-component strategy to determine the optimal number of components required in the system.

3 MONO- COMPONENT STRATEGY

3.1 Description

In a finite time, horizon, a single-component system is subject to failure according to a known reliability law with a constant failure rate. To address this issue, a corrective maintenance action is necessary, which involves replacing the failed component with a new one. It's worth noting that in this scenario, the cost of recycling the failed component is considered an environmental cost.

3.2 Analytical model

3.2.1 Notation

Table 1: Notation mono-component system strategy

Notation	
H	Finite horizon
C_c	Unit component cost
C_m	Unit maintenance cost according to the replacement task
λ	Failure rate of one component
C_{rc}	Unit recycle cost of one component
CT_{mono}	Average total cost of the mono-component system (acquisition, maintenance, recycling)
N	Number of replacements on horizon H

3.2.2 Model

An analytical development is carried out to determine the average total cost of the traditional strategy throughout a specified time horizon, H. This total cost encompasses the initial equipment installation cost, maintenance expenses, and environmental costs.

Cost of acquisition :

$$CAmono = C_c + C_m + C_{rc} \quad (1)$$

The degradation of the component is considered to follow an exponential law. Therefore, the function of the number of replacements can be determined by integrating the failure rate from 0 to H. The resulting function is shown below:

$$N = \lambda \times H \quad (2)$$

To calculate the total maintenance cost for the single-component strategy, the following costs are added together: the cost of acquisition, recycling, and intervention, multiplied by the number of replacements required within the specified horizon, H.

$$CT_{mono} = C_c + (C_c + C_m + C_{rc}) \times \lambda \times H \quad (3)$$

4 MULTI-COMPONENT STRATEGY

4.1 Description

The strategy involves setting up a system with n identical components on standby, connected in series via a switching system. These components are identical to those used in the single-component system. As the system experiences an increasing failure rate over time, an age-type preventive maintenance policy, known as "as good as new," is implemented.

If a breakdown occurs before the specified time, T (the date of preventive maintenance), the entire system is replaced with a new one, incurring a total cost that includes the cost of the switching circuit, n multiplied by the cost of each component, and the cost of recycling associated with the multi-component maintenance strategy system for corrective action. This is classified as a corrective maintenance action, which includes replacement costs at failure and the cost of recycling failed components.

If the system does not experience a breakdown and reaches the designated time, T, a preventive maintenance action is required. This involves verifying and inspecting the switching system and making a change if an anomaly is detected in one of the n standby components (0≤n1<n). In this case, the cost of component recycling for failed components should be taken into consideration. The cost of preventive maintenance may vary depending on the anomalies detected, but an average cost is estimated for each preventive maintenance action, including a fixed cost for the preventive maintenance itself and a fixed cost for component recycling.

Note that after each preventive or corrective maintenance action, the system is considered "as good as new." An optimal date, T*, can be determined to carry out a preventive maintenance action to minimize maintenance costs.

4.1 Analytical model

4.1.1 Notation

Table 2: Notation multi-component maintenance strategy

Notation	
n	Number of possible components adopted in redundancy system
H	Finite horizon
Csw	Cost of switching component of redundancy system (system stand-by)
Cc	Unit component cost
Cm	Unit maintenance cost according to the replacement task
λ	Failure rate of one component
λdc	Failure rate of switching component
Crc	Unit recycle cost of one component
Crcr	Unit recycle cost according to corrective maintenance action applied to redundancy system
Crpr	Unit recycle cost according to preventive maintenance action applied to redundancy system
Mp	Unit cost of preventive maintenance action for redundancy system
Mc	Unit cost of corrective maintenance action for redundancy system
T*	Optimal preventive maintenance date for the system multi-component maintenance strategy minimizing maintenance costs
CTMs*	Optimal average total cost of maintenance actions for the multi-component maintenance strategy system by adopting T*
CTmono	Average total cost of the mono-component system (acquisition, maintenance, recycling)
CTmulti	Average cost of the multi-component system (acquisition, maintenance, recycling)

The system is comprised of n elements in passive redundancy (stand-by) connected via a switching circuit. When the initial component fails, the standby component takes over.

The failure rate of the components is identical.

The failure rate of the components and that of the switching component are considered constant and are equal to λ and λDC respectively.

To determine the optimal date, T*, for preventive maintenance, the system's reliability can be calculated using the following expression:

$$Rsys(t) = e^{-(\lambda+\lambda DC).t}\sum_{i=2}^{n-1}\frac{(\lambda.t)^i}{i!} \tag{4}$$

The system failure rate is written as:

$$\lambda sys(t)=\frac{-\frac{d\,Rsys}{dt}}{Rsys(t)} \tag{5}$$

Average total cost of age-type maintenance actions “as good as new” is given by the following expression:

$$CTM = \left(\begin{array}{c} R_{sys}(T)\times(Mp+Crcr) \\ +\left(1-R_{sys}(T)\right)\times \\ \left(\begin{array}{c}((n\times Cc)+Csw) \\ +Cm+Crpr\end{array}\right)\end{array}\right)\Bigg/\left(\int_0^T R_{sys}(u)\,du\right) \tag{6}$$

For each value of n (n≥2), we optimize the CTMs to determine T* and its corresponding CTMs*. We activate the multi-component maintenance strategy system and adhere to the planned preventive maintenance schedule for the designated horizon, H. If a breakdown occurs before T*, we perform corrective maintenance while considering the cost of recycling failed components. The recycling cost is also taken into account during preventive maintenance.

Cycle duration:

$$\int_0^{T*} R_{sys}(u)\,du \tag{7}$$

The number of cycles on H:

$$Ent\left(\frac{H}{\int_0^{T*} R_{sys}(u)\,du}\right) \tag{8}$$

To determine the number of cycles on the H horizon, we divide the H horizon by the duration of a single cycle.

The cost of maintenance and recycling over a cycle is estimated by:

$$\begin{array}{c} R_{sys}(T^*)\times(Mp+Crcr) \\ +\left(1\text{-}R_{sys}(T^*)\right)\times(((n\times Cp)+Csw) \\ +Ci+Crpr) \end{array} \tag{9}$$

Between the last preventive maintenance action and the end of the H horizon, there is a risk of failure, so we have an estimated cost of:

$$\begin{array}{c}\left(1\text{-}R_{sys}\left(H\text{-}\left(\begin{array}{c}Ent\left(\frac{H}{\int_0^{T^*}R_{sys}(u)\,du}\right) \\ \times\int_0^{T^*}R_{sys}(u)\,du\end{array}\right)\right)\right) \\ \times(((n\times Cc)+Csw)+Ci+Crpr)\end{array} \tag{10}$$

If a failure occurs between the last preventive maintenance action and the end of the horizon H, the corrective maintenance cost is estimated using the aforementioned expression.

The acquisition cost of a multi-component maintenance strategy system with n components at t=0:

$$CAmulti = (n\times Cc) + Csw \tag{11}$$

The acquisition cost of the multi-component maintenance strategy system equals the cost of acquiring a single component divided by the number of components plus the cost of the switching system.

The estimated total cost of the multi-component maintenance strategy (including maintenance, recycling, and acquisition) is :

$$\begin{array}{c} CTmulti\,(T,n) = \\ ((n\times C_c)+C_{sw}) \\ +Ent\left(\frac{H}{\int_0^{T^*}R_{syst}(u)\,du}\right) \\ \times(R_{syst}(T^*)\times(M_p+C_{rcr}) \\ +\left(1-R_{syst}(T^*)\right) \\ \times(((n\times C_c)+C_{sw})+C_m+C_{rpr})) \\ +\left(\begin{array}{c}1-R_{syst} \\ \times\left(\begin{array}{c}H-Ent\left(\frac{H}{\int_0^{T^*}R_{syst}(u)\,du}\right) \\ \times\int_0^{T^*}R_{syst}(u)\,du^*\end{array}\right)\end{array}\right) \\ \times\left((n\times C_c)+C_{sw}\right. \\ \left.+C_i+C_{rpr}\right) \end{array} \tag{12}$$

4.1.2 Numerical example

To compare the total costs of the two strategies, we utilized the numerical solution software "MATHEMATICA" to determine the overall costs and to identify the optimal number of components, n, and the optimal date, T, for preventive maintenance actions.

The following table displays the numerical data:

Table 3: Numerical example data

Nmax	11 composants
H	180
Csw	50
Cc	100
Cm	90
Crm	5
λ	0.2
λdc	0.005

4.1.3 Numerical results

The results obtained are detailed in the following tables:

Results of the 1st model (mono-component strategy)

Table 4: Results of the 1st model

H	CTmono
180	7 120

Under the aforementioned conditions, the total cost of the single-component strategy is 7,120 monetary units.

Results of the 2nd model (multi-component strategy)

Table 5: Results of the 2nd model

n	T	CTmulti
11	41	5 641,24

Under identical conditions, the multi-component maintenance strategy recommends using 11 reserve components and performing preventive maintenance at a period of T=41, resulting in a total cost of 5 641,24 monetary units.
In this scenario, the multi-component maintenance strategy proves to be more cost-effective than the single-component strategy.

5 Sensitivity analysis

5.1 Variation in the intervention cost

The following table demonstrate how changes in the intervention cost affect the multi-component maintenance strategy.

Table 6: variation of the intervention cost

n	T	CTmulti	Cm
4	49	4 030,72	1
5	48	4 274,25	5
11	**41**	**5 641,24**	**90**

The results show that the overall cost of the multi-component maintenance strategy grows in direct proportion to the intervention cost, as seen by the rise in CTmulti (total cost) from 4 030.72 to 5 641.24 when the intervention cost rises from 1 to 90.
The strategy suggests increasing the amount of reserve components to counteract this impact and lower overall expenses. Witch lessen the requirement for interventions since faulty primary components can be swiftly replaced by reserve components. The maintenance team can minimize related expenditures including labor, equipment, and materials by minimizing the requirement for interventions.

5.2 Variation of the failure rate of a component

This section illustrates how the strategy developed is affected by the component failure rate.

Table 7: Variation of the failure rate of a component

n	T	CTmulti	λ
4	49	4 030,72	0,05
7	48	4 879,71	0,1
11	**41**	**5 641,24**	**0,2**
11	18	9 156,32	0,4

The overall cost of the maintenance plan rises in direct proportion to the failure rate λ, as seen by the increase in CTmulti from 4,030.72 to 9,156.32 when the failure rate rises from 0.05 to 0.4.

The strategy suggests increasing the quantity of spare components to lessen the effects of a high component failure rate. The latter lessens downtime and lowers the likelihood of component failures, which helps to achieve a high availability rate.

The data presented in Table 7 also shows that depending on the number of components (n) and the time between interventions (T), the failure rate's effect on the maintenance strategy's overall cost varies.

5.3 Variation of the failure rate of the switching system

In this section, we present the results of the sensitivity analysis conducted on the failure rate of the switching system, which is the final parameter investigated.

Table 8: variation of the failure rate of the switching system

n	T	CTmulti	λdc
11	43	4 466,82	0,001
11	**41**	**5 641,24**	**0,005**
6	39	19 497,20	0,05
4	19	70 062,00	0,5

The sensitivity analysis's findings, which are shown in Table 8, show that the overall cost of the maintenance strategy falls when the switching system's failure rate is low. This implies that there is a lesser likelihood of component failures in the system, which means fewer maintenance interventions and lower total costs.

The strategy suggests increasing the quantity of reserve components and delaying preventative maintenance procedures in order to lessen the effect component failures have on the system. The risk that a component failure will impair the system's performance is decreased by increasing the number of reserve components, leading to fewer maintenance interventions and lower costs.

6 Comparison

To validate the relevance of our results, we conducted a comparative cost analysis of the two strategies based on two key parameters. The following tables illustrate the results obtained:

6.1 *Effect of intervention cost*

Table 9: Effect of intervention cost

Cm	CTmono	CT**multi**
1	3 916,00	4 030,72
5	4 060,00	4 274,25
90	**7 120,00**	**5 641,24**
180	10 360,00	5 917,21

According to the findings in Table 9, the mono-component method has a lower overall cost than the multi-component strategy at lower intervention costs. However, the multi-component technique becomes more cost-effective as the intervention cost rises. This shows that systems with high intervention costs, where the cost of downtime due to component failures is significant, are better suited for the multi-component strategy.

6.2 *Effect of component failure rate*

We also conducted a comparison of the costs of the two strategies by varying the failure rate of the components. The results are presented in the following table:

Table 10: Effect of component failure rate

λ	Ctmono	CT**multi**
0,05	1 855,00	4 030,72
0,1	3 610,00	4 879,71
0,2	**7 120,00**	**5 641,24**
0,4	14 140,00	9 156,32
0,8	28 180,00	16 063,50

The comparison in Table 10 demonstrates that when component failure rates are high, multi-component maintenance strategies are more cost-effective. The table demonstrates that as component failure rates rise, the total cost of the mono-component strategy rises quickly whereas the cost of the multi-component method rises considerably more gradually. As a result, it is advised to use a multi-component maintenance method when component failure rates are significant. It is also advised to increase the quantity of reserve components in order to guarantee long system operation times.

7 CONCLUSION

This article presents a study on developing a partial multi-component maintenance strategy that takes into account economic, environmental, and reliability constraints. The aim of the study is to determine the optimal number of reserve components to use in the multi-component maintenance strategy and determine the optimal date of preventive maintenance actions to minimize the total cost of maintenance over a finite horizon. The article compares the total cost of the multi-component maintenance strategy with the single-component strategy and provides an analytical model and a numerical example to illustrate the two strategies.

The results of the study show that the multi-component maintenance strategy is more economical under the tested conditions. The article also includes a sensitivity study that varies three parameters to validate the results obtained. The study is significant because it contributes to the limited research on multi-component maintenance strategy.

In summary, the article offers valuable insights for professionals in the maintenance field and presents a novel approach to multi-component maintenance strategy that considers economic, environmental, and reliability constraints. The analytical model and numerical example provide a useful framework for practitioners to adopt the multi-component maintenance strategy and optimize preventive maintenance actions. The study's findings can help organizations reduce maintenance costs and improve the efficiency of their operations.

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