Optimal performance of a stochastic repair and replacement model with imperfect Repairs

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Abstract

The optimal performance of a repairable system where failure results in either an imperfect repair or replacement under exponential time between failures and repair times is discussed in this study. We develop a constrained stochastic nonlinear optimization model with capital, repair, and downtime costs constituting the three cost categories of the objective function. In this context, a closed expression for the optimal minimum cost is developed, along with analytical expressions for a variety of parameters, including repair and replacement rates.

Key words
nonlinear optimization, down time, minimum cost, imperfect repai

1. Introduction

Currently, industrial organizations are confronted with several difficulties that risk their financial success. During production, manufacturing systems are subjected to a variety of disruptions, including deterioration, random failures, poor maintenance techniques, and quality decline, among others, all of which have a significant impact on the overall performance of such systems. As a result, appropriate production and maintenance techniques are essential for limiting the effects of such unpredictably disruptive events.

In recent years, product quality has become a significant dimension that has steadily been incorporated into the field of production systems. Because effective quality methods are directly linked to production and maintenance, integrated models including the three core functions of production, quality, and maintenance have lately delivered better outcomes than traditional models that address these activities independently. Several other issues, such as degradation, have a negative impact on the system's performance. In real life, not only is performance important, but so is cost, and systems also behave in an unpredictable manner.

During their operational life, Industrial systems are subject to repair actions when they fail during their operating life. The goal of a repair action is to decreases the system's failure rate and extend its useful life. The system's inherent age as well as the effectiveness of repair must be considered during the maintenance process. In most cases, repair efficiencies are assumed to be minimal, perfect, or imperfect. The system is returned to its operating state just before the failure in minimal maintenance. The goal of a perfect repair is to return the system to its original state which is as good as new. Meanwhile, these assumptions are not necessarily feasible for a repairable system because the system can be effectively repaired but not renewed. This is referred to as imperfect repair.

In this paper, we aim to develop an optimization model for a repairable system with identical components that, upon failure, is either replaced or imperfectly repaired, but with varying probability. The expressions for the optimal values for many critical metrics such as repair and failure rates are determined. Furthermore, the expression for the minimum total cost is derived, noting that three cost components are incorporated including purchase cost, repair cost, and downtime cost total.

2. Literature Review

Barlow (1965) used the Markov process to examine system availability and presented the principles of mathematical theory of reliability. To put it another way, maintenance is used to improve equipment reliability by preventing unexpected malfunctions, decreasing unscheduled downtimes, and lowering maintenance costs

(Alsyouf, 2007). Most factories, when it comes to production, are made up of many different machines. They normally have varying levels of reliability, safety, and failure rates. Different machines require different maintenance plans to maintain a degree of dependability and availability that is acceptable (Wang, Chu, & Wu, 2007). This is especially critical in a multi-factory manufacturing network, where an unforeseen event could occur.

A general method for enhancing maintenance of multi-component systems with degrading interactions was described by Rasmekomen and Parlikad (2014). Regression approaches and general path degradation modeling were used to characterize the degradation interactions in a degradation model for M-component systems where N (NM) components are prone to degradation interactions. Levitin et al. (2018) looked at heterogeneous 1-out-of-N warm standby systems with internal component failures and operational components that are also subjected to external shocks. a comparable decline through the passage of time. As a result, a preventative replacement policy is considered, in which the operational component is replaced after a specific number of shocks. The instantaneous availability expression is derived. Then, over a finite time horizon, an optimization problem for a replacement policy that maximizes total mission availability is stated and solved. For a two-component system with stochastic and economic dependencies, a model of a condition-based maintenance policy was constructed (Do et al. (2019). Because of the stochastic dependency, each component's rate of deterioration is influenced by both its own state and the state of the other component. To determine the ideal values of the choice variables, a cost model is created.

Liua et al. (2020) described relevant asymptotic features for steady-state virtual aging processes in their study. It is demonstrated that the age, residual lifespan, and spread limiting distributions that define an ordinary renewal process may be generalized to the stable virtual age process. Wang et al. (2020) examined imperfect preventive maintenance (PM) policies with untimely executions for infinite and finite planning horizons, respectively. To reduce the long-run average cost rate, the goal is to identify the ideal number of PM actions and related PM interval. They modelled optimization of two untimely PM policies and investigated analytically how untimely executions affect the best PM choices and associated maintenance costs.

Volf (2021) was concerned with maximizing a technical device's preventative maintenance program. The main objective is to develop a model for determining the device's optimal lifetime while minimizing maintenance expenses. Zhao et al. (2021) examined the performance of a cold standby system with two components that are subjected to δ -shocks and imperfect repairs and had varied reliability characteristics. Under shocks and incomplete repairs, geometric process models are used to characterize the lifetime and repair time. To quantify the system's economic performance, an equation for the long-run cost per unit time is also generated. For a two-unit series system. Gan et al. (2021) developed a novel maintenance technique for systems that experience normal degradation and shock. The shock process is a non-homogeneous Poisson process, and the dependence between normal degradation and shock occurrence intensity is considered using a changing factor. The system reliability is separated into three stages, each of which has its own set of maintenance operations. The proposed maintenance policy is also contrasted with two other maintenance policies. The findings of the comparison reveal that the proposed strategy is both necessary and effective. For multi-component systems, Fu and Wang (2021) presented a periodic maintenance strategy in which numerous component reallocations and system overhauls are jointly conducted periodically at set times, and components are minimally repaired immediately after failures in a life cycle. For repairable systems with dependent failure processes, Liu et al. (2021) presented a condition-based maintenance model. Several maintenance actions, including inspection, preventive maintenance, and corrective maintenance, were evaluated for their negative or positive consequences. In this case, a vector space covered by the degradation level, deteriorate rate, and hard failure threshold is built to intuitively quantify the consequences of maintenance measures.

The Wiener process was used by Xinlong et al. (2022) to describe the process of a random degradation of a system that increases the number of maintenance calls. Has developed an imperfect preventive maintenance optimization technique with the purpose of obtaining the optimum preventive maintenance threshold, inspection cycle, and optimal number of maintenances, with the long-term maintenance cost rate as the target. Finally, a Monte Carlo simulation was utilized to numerically solve the problem and examine the impact of each parameter on the best solution. It can be used as a guide for making decisions while designing maintenance policies. Lin et al. (2022) designed a multicomponent model optimization reliability model under s-dependent competing risks. The goal is to find the best reliability threshold as well as the best number of PM cycles at the lowest total predicted maintenance cost rate. Zhang et al (2022) developed a combination optimization problem of condition-based maintenance policy and buffer capacity for a two-unit series system in their work. The semi-Markov process was used to examine the probabilities of the system's transition states under imperfect repairs.

Moreover, an example was presented using simulation example to illustrate the superiority of the proposed joint optimization strategy. Lujie et al. (2022) developed a stochastic durations multi-mission selected maintenance and repairpersons assignment model. The model is then transformed into an optimization problem with the goal of minimizing the predicted total cost while maintaining a certain level of reliability and working with limited maintenance resources. The optimization challenge was solved using a genetic algorithm.

3. Methodology

We try to identify the best parameters for a series system with numerous components that go through n failures before complete regeneration in this paper. An optimization model is developed; the model is a non-linear programming problem with inequality constraints, and the general formula is:

Minimize $z = f(X)$ (1)

Subject to g(X) >= 0

X>=0

The Khun Tucker criteria will be utilized to determine the optimal solution, in this case, where the set of inequality constraints, g(X) >= 0 can be converted to equalities by using the proper nonnegative slack variables. Then, to satisfy the non-negativity conditions, Let $S_i^2 >= 0$, the square of the slack variable subtracted from the i^{th} constraint. Next, Define,

$\boldsymbol{S} = (S_1, S_2, \ldots, S_j)^T$ and $\boldsymbol{S^2} = (S^2_1, S^2_2, \ldots, S^2_j)^T$ be the slack variable vector and its corresponding square values vector, respectively. The Lagrangean function is given by:

$$\tilde{L}(\mathbf{X}, \mathbf{S}, \bar{\xi}) = f(\mathbf{X}) - \bar{\xi}\left[\mathbf{g}(\mathbf{X}) - \mathbf{S^2}\right]$$

(2)

where $\bar{\xi}$ represents the constraints vector $\mathbf{g}(\mathbf{X}) \geq \mathbf{0}$. of Lagrange multipliers. The following is produced by taking the partial derivatives $\tilde{L}$ of with respect to $\mathbf{X}, \mathbf{S}, \bar{\xi}$ and setting them to zeros: Depending on

$$\frac{\partial \tilde{L}}{\partial \mathbf{X}} = \nabla f(\mathbf{X}) - \bar{\xi}\, \nabla \mathbf{g}(\mathbf{X}) = \mathbf{0}$$

(3)

$$\frac{\partial \tilde{L}}{\partial S_i} = 2\xi_i S_i = 0 \qquad i = 1, 2, \ldots\ldots, \hat{I}$$

$$\frac{\partial \tilde{L}}{\partial \bar{\xi}} = -\left[\mathbf{g}(\mathbf{X}) - \mathbf{S}^2\right] = \mathbf{0}$$

The following is derived from the above set of equations

$$\xi_i g_i(\mathbf{X}) = 0 \qquad i = 1, 2, \ldots, \hat{I} \tag{4}$$

$$\nabla f(\mathbf{X}) - \bar{\xi}\, \nabla \mathbf{g}(\mathbf{X}) = \mathbf{0}$$

(5)

$$\xi_i g_i(\mathbf{X}) = 0 \qquad i = 1, 2, \ldots, \hat{I}$$

$$\mathbf{g}(\mathbf{X}) \geq \mathbf{0}$$

$$\bar{\xi} \geq 0$$

$$Minimize\ \ z = f(\lambda, \mu) = \frac{C_1}{\lambda} + C_2\mu + C_3(1 - A)$$

$$A \geq \rho_1$$

(6)

Subject To

$$\mu - \lambda \geq 0$$
$$\lambda \geq 0$$
$$\mu \geq 0$$

Where
C_1: The initial purchase per component, it is associated with the failure rate of the system.
C_2: The repair cost.
C_3: The steady state down time cost.
ρ_1: A given minimum desired level of availability.
λ: Failure rate, μ: Repair rate.
ρ_1: A given minimum desired level of availability.
λ = failure rate, μ= repair rate

3.1 Probabilistic imperfect Repair

Unlike standard replacement mechanism where a failed component is replaced after a certain number of imperfect repairs, this process adds complexity by assuming that after each failure, the failed component is either fully replaced by a new one and thus returns to state 1 with probability p or is imperfectly repaired with probability (1-p) and transitions to the next state. Figure 1 depicts the entire system, displaying the various transitions between the various stages, with the rectangle shapes representing functioning (up) states and the oval shapes representing failed (down) ones. In this process, the total number of states is 2n+2.

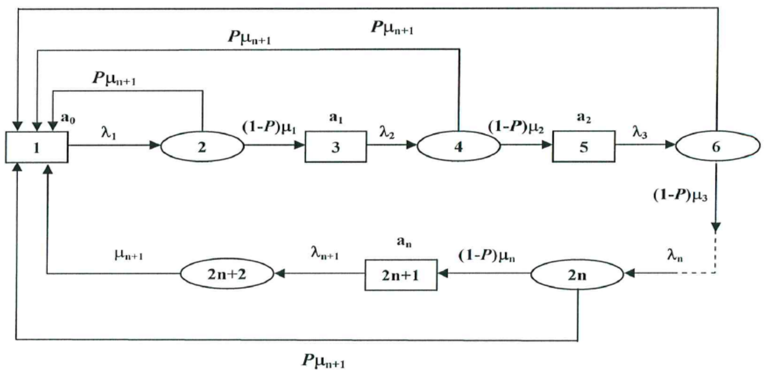

Fig.1. A stochastic repair and replacement model for a single-component system.

The performance of this system is measured by the steady state availability, it has the following structure (Hajeeh, 2004):

$$A = \frac{\left[\frac{1}{\lambda_1} + \sum_{i=2}^{n+1} \frac{1}{\lambda_i} \prod_{j=1}^{n-1} \left(\frac{(1-p)\mu_j}{(1-p)\mu_j + p\mu_{n+1}} \right)\right]}{\left[\frac{1}{\lambda_1} + \sum_{i=2}^{n+1} \frac{1}{\lambda_i} \prod_{j=1}^{n-1} \left(\frac{(1-p)\mu_j}{(1-p)\mu_j + p\mu_{n+1}} \right) + \sum_{i=1}^{n+1} \frac{1}{\mu_i'} \prod_{j=1}^{i} \left(\frac{(1-p)\mu_j}{(1-p)\mu_j + p\mu_{n+1}} \right) + \frac{1}{\mu_{n+1}} \prod_{j=1}^{n} \left(\frac{(1-p)\mu_j}{(1-p)\mu_j + p\mu_{n+1}} \right)\right]}$$

After each failure, the system's performance deteriorates, and the failure rate rises, $\lambda_{i+1}>\lambda_i$. If the initial failure rate is λ_1, then consecutive failure rates are $\lambda_{i+1}=\varphi_{i+1}\lambda$,, where $\lambda_1=\lambda$, $\varphi_{i+1}>= =\varphi_i$ and $\varphi_1=1$, i =1,,n. Similarly, the repair rates are expressed as $\mu_{i+1}=\psi_{i+1}\mu$, where μ is the replacement rate and $\psi_{i+1}<=\psi_i$ since the repair rate drops as the number of failures increases, i =1,,n-1. The above expression is recast as follows, using the relations

$$A=\frac{\frac{1}{\lambda}\left[\frac{1}{\phi_1}+\sum_{i=2}^{n+1}\frac{1}{\phi_i}\prod_{j=1}^{i-1}\left(\frac{(1-p)\psi_j\mu}{(1-p)\psi_j\mu+p\psi_{n+1}\ \mu}\right)\right]}{\left\{\begin{array}{l}\frac{1}{\lambda}\left[\frac{1}{\phi_1}+\sum_{i=2}^{n+1}\frac{1}{\phi_i}\prod_{j=1}^{i-1}\left(\frac{(1-p)\psi_j\mu}{(1-p)\psi_j\mu+p\psi_{n+1}\mu}\right)\right]\\+\frac{1}{\mu}\left[\sum_{i=1}^{n-1}\frac{1}{\psi_{i+1}}\prod_{j=1}^{i+1}\left(\frac{(1-p)\psi_j\mu}{(1-p)\psi_{j\mu}+p\psi_{n+1}\mu}\right)+\frac{1}{\psi_{n+1}}\prod_{j=1}^{n}\left(\frac{(1-p)\psi_j\mu}{(1-p)\psi_j\mu+p\psi_{n+1}\ \mu}\right)\right]\end{array}\right\}}$$

(7)

If the numerators of the above expression are designed as α and the second expression in the denominators is designed as β, the above expression is simplified to:

$$A=\frac{\frac{\alpha}{\lambda}}{\frac{\alpha}{\lambda}+\frac{\beta}{\mu}}=\frac{\alpha\mu}{\alpha\mu+\beta\lambda}$$

(8)

Where $\alpha=\left[\frac{1}{\phi_1}+\sum_{i=2}^{n+1}\frac{1}{\phi_i}\prod_{j=1}^{i-1}\left(\frac{(1-p)\psi_j\mu}{(1-p)\psi_j\mu+p\psi_{n+1}\ \mu}\right)\right]$

And $\beta=\left[\sum_{i=1}^{n-1}\frac{1}{\psi_{i+1}}\prod_{j=1}^{i+1}\left(\frac{(1-p)\psi_j\mu}{(1-p)\psi_{j\mu}+p\psi_{n+1}\mu}\right)+\frac{1}{\psi_{n+1}}\prod_{j=1}^{n}\left(\frac{(1-p)\psi_j\mu}{(1-p)\psi_j\mu+p\psi_{n+1}\ \mu}\right)\right]$

The general optimization Model for a component series is of the following structure:

$$Minimize\ \ z=f(\lambda,\mu)=\frac{C_1}{\lambda}+C_2\mu+C_3\left(1-\frac{\alpha\mu}{\alpha\mu+\beta\lambda}\right)$$

Subject To

$$\mathrm{A}=\left(\frac{\alpha\mu}{\alpha\mu+\beta\lambda}\right)\geq\rho_1$$
$$\mu-\lambda\ \geq 0$$
$$\lambda\ \geq 0$$
$$\mu\ \geq 0$$

Where all the parameters are as was defend in the previous section

$$Minimize\ \ z=f(\lambda,\mu)=\frac{C_1}{\lambda}+C_2\mu+C_3\left(1-\frac{\alpha\mu}{\alpha\mu+\beta\lambda}\right)-\xi_1\left(\frac{\alpha\mu}{\alpha\mu+\beta\lambda}-\rho_1\right) \qquad (9)$$

Where ξ_i: Lagrange multiplier for the i^{th} inequality constraint.

The Khun Tucker conditions for the above optimisation problem (16) is:

$$\frac{\partial f}{\partial \lambda} = -\frac{C_1}{\lambda^2} + C_3\left(\frac{\alpha\beta\mu}{(\alpha\mu+\beta\lambda)^2}\right) + \xi_1\left(\frac{\alpha\beta\mu}{(\alpha\mu+\beta\lambda)^2}\right)$$

(10)

$$\frac{\partial f}{\partial \mu} = C_2 + C_3\left(\frac{-\alpha\beta\alpha\lambda}{(\alpha\mu+\beta\lambda)^2}\right) - \xi_1\left(\frac{\alpha\beta\lambda}{(\alpha\mu+\beta\lambda)^2}\right)$$

(19)

$$\frac{\partial f}{\partial \xi_1} = \left(\frac{\alpha\mu}{\alpha\mu+\beta\lambda} - \rho_1\right) = 0 \tag{11}$$

Therefore, from (20) $\left(\frac{\alpha\mu}{\alpha\mu+\beta\lambda} - \rho_1\right) = 0 \Rightarrow \frac{\alpha\mu}{\alpha\mu+\beta\lambda} = \rho_1$. Let $\rho = (\rho_1/(1-\rho_1))$ and rearrange then: $\mu=\rho\beta\lambda/\alpha$

Now substituting $\rho\beta\lambda/\alpha$ for μ in equations (18) and (19) and adding the two results in the following:

$$\frac{\partial f}{\partial \lambda} = -\frac{C_1}{\lambda^2} + C_3\left(\frac{\beta\beta\rho}{\lambda(\beta\rho+\beta)^2}\right) + \xi_1\left(\frac{\beta\beta\rho}{\lambda(\beta\rho+\beta)^2}\right)$$

$$\frac{\partial f}{\partial \mu} = C_2 + C_3\left(\frac{-\alpha\alpha\beta}{\lambda(\beta\rho+\beta)^2}\right) - \xi_1\left(\frac{\alpha\alpha\beta}{(\beta\rho+\beta)^2}\right)$$

Adding and manipulation results in

$$C_2 - \left[\frac{C_1}{\lambda^2}\left(\frac{\rho\alpha}{\beta}\right)\right] \Rightarrow \lambda^2 = \frac{C_2\beta}{C_1\rho\alpha} \Rightarrow \lambda = \sqrt{\frac{C_2\beta}{C_1\rho\alpha}}$$

Hence since $\mu = \frac{\beta\lambda\rho}{\alpha}$, then:

$$\mu^* = \frac{\beta\rho}{\alpha}\sqrt{\frac{C_2\beta}{C_1\rho\alpha}} \text{ and } \xi_1^* = \frac{C_1}{\lambda^2}\left(\frac{\alpha(\mu+\rho\mu)^2}{\beta\mu}\right) - C_3$$

Thus, the optimal solution is:

$$\lambda^* = \sqrt{\frac{C_2\beta}{C_1\rho\alpha}};\ \mu^* = \frac{\beta\rho}{\alpha}\sqrt{\frac{C_2\beta}{C_1\rho\alpha}};\ \xi_1^* = C_1\rho(1+\rho)^2\sqrt{\frac{C_1\alpha\rho}{\beta C_2}} - C_3;\ z^* = C_1\sqrt{\frac{C_1\rho\alpha}{C_2\beta}} + C_2\frac{\beta}{\alpha}\sqrt{\frac{C_2\rho\beta}{C_1\alpha}} + C_3\left(\frac{1}{\rho+1}\right)$$

(12)

Where $\alpha = \left[\frac{1}{\phi_1} + \sum_{i=2}^{n+1}\frac{1}{\phi_i}\prod_{j=1}^{i-1}\left(\frac{(1-p)\psi_j\mu}{(1-p)\psi_j\mu + p\psi_{n+1}\ \mu}\right)\right]$

And $\beta = \sum_{i=1}^{n+1}\frac{1}{\psi_i}\prod_{j=1}^{i}\left(\frac{(1-p)\psi_j\mu}{(1-p)\psi_j\mu + p\psi_{n+1}\ \mu}\right) + \frac{1}{\psi_{n+1}}\prod_{j=1}^{n}\left(\frac{(1-p)\psi_j\mu}{(1-p)\psi_j\mu + p\psi_{n+1}\ \mu}\right)$

And ξ_1 id the Lagrange multipliers λ^*, μ^*,ξ^*, and z^* are the optimal values for the failure rate, repair rate, Lagrangian multiplier, and objective function, respectively

4. Results and Discussion

The optimal parameters are obtained from equations (9–11) and are provided in equation (12). The stochastic repair and replacement model, which was the subject of the study, is a generic model from which alternative models with a similar structure can be deduced. According to this approach, the process is replaced if the probability of replacement is 1. following each failure

The procedure becomes imperfect repair and replacement if we set the replacement probability value to 0. (Hajeeh, 2022). The model involves probabilistic repair and replacement for probability values between 0 and 1. The models with $p = 1$ and $p = 0$ are clearly the worst when comparing their performances; nevertheless, models where p is between 0 and 1 are better than the imperfect model and worse than the total replacement model (perfect repair). Even while performance is the key criterion for choosing a system, cost is just as significant. We are unable to distinguish between the various models in this regard and select the best one. In this study three categories are considered, namely purchase, repair, and down time costs.

In general, we don't prefer to replace a broken component with a new one because that would cost a lot of money, and we also don't like to keep repairing broken components. Thus, imperfect repair systems are the most advantageous, followed by stochastic repair and replacement, and then the ideal model, if all characteristics, variables, and costs are the same.

5. Conclusion and Future Directions

In this paper, a general optimal model for stochastic repair and replacement is developed, from which the performance of various systems can be produced. Engineers and decision makers should carefully examine all the parameters before choosing any system. It has been noted that the optimization model is more intricate, and careful research is required to identify the best options and parameters. Additionally, standby and parallel setups are more intricate and challenging to solve than series ones.

Future studies should consider complicated systems, with different failure modes, and multiple components. The failure and repair rates of systems that follow different distributions, such as the Weibull and Beta Distributions, among others, must also be considered. Simulation needs to be considered for more complicated systems.

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Biography

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6.5