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Reliability Modelling and Cost-Benefit Analysis of a System of Non-Identical Units with Priority to Replacement over Preventive Maintenance

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Abstract

The primary objective of this paper is to study and concentrate on the prioritization of replacement actions over preventive maintenance strategies within non-identical unit systems, seeking to strike an optimal balance between cost-effectiveness and system dependability. Our approach combines mathematical modeling, data analysis, and simulation to elucidate the intricate relationships between maintenance strategies, system reliability, and cost efficiency. Initially, the main unit is operative whereas the duplicate unit is at cold standby. The system undergoes the preventive maintenance after maximum operation time. Single server visits the failed unit immediately for conducting repair, replacement. The expressions for some important reliability measures such as Transition probabilities, mean-sojourn time, MTSF, Availability and Profit of the system model have been derived in graphical form.

***Keywords* —** Reliability Modelling, Cost Benefit Analysis, Non-identical Units, Different Repair strategies, Maximum Operation Time

I. INTRODUCTION

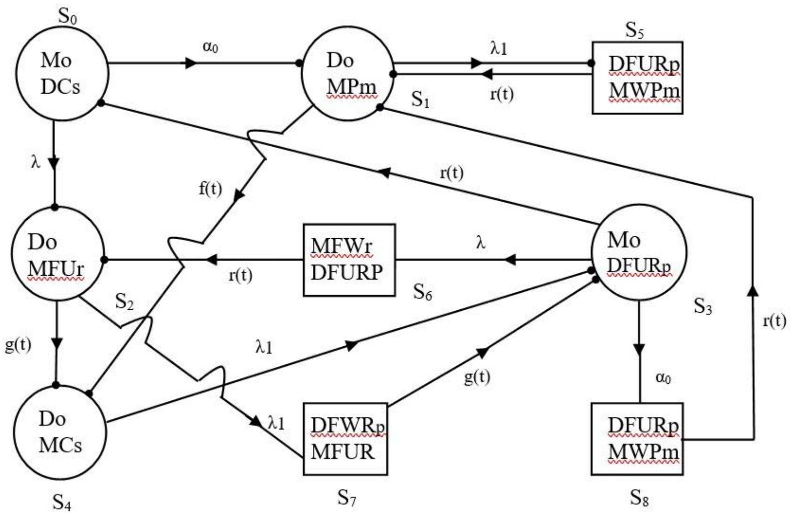
In an era characterized by rapid technological advancements and heightened competition, the reliability and cost-effectiveness of complex systems are of paramount importance to industries and organizations across the globe. One fundamental aspect of managing the reliability of such systems is the judicious allocation of resources between two crucial maintenance strategies: preventive maintenance (PM) and replacement. This paper embarks on an exploration of this critical issue, focusing on a specific scenario—systems composed of non-identical units—where the allocation of maintenance resources becomes an intricate problem.

The allocation of resources for maintenance activities in a system composed of non-identical units poses a unique set of challenges. Unlike homogeneous systems where all units are identical, non-identical systems exhibit varying degrees of performance degradation over time, making it imperative to prioritize maintenance actions effectively. In this context, one common strategy is to emphasize replacement over preventive maintenance, given the potential for significant cost savings and improved system reliability. Many researchers including Rander and kumar (1994) performed the cost analysis of a two Dissimilar Cold standby System with preventive maintenance and replacement of standby unit. P Mohanavadivu (1997) evaluated the same configuration with different repair strategies. Chander et. Al. (2004 – 2005) stochastically analyzed the system of non-identical units. Malik and Upma (2016) performed the cost benefit analysis with different repair policies. Deswal (2020) evaluated the performance measures using SMP and RPT.

The main emphasis of the present paper is to analyze and compare the cost-effectiveness of replacement strategies versus preventive maintenance strategies in the context of non-identical systems. We have given preference to replacement of the duplicate unit over PM of the main unit. There are two modes of the units- operative and complete failure. All repair activities including preventive maintenance, replacement and repair of the units are carried out by a single server who visits the system without any delay. After a specific operation of time, the PM of the main unit is conducted. The main unit under goes for repair at its complete failure while replacement of the duplicate unit is made by the server with a new unit at its completer failure. This research work will provide practical recommendations and guidelines for decision-makers in industries and organizations dealing with complex systems composed of non-identical units. The reliability measures are obtained in steady state by adopting the techniques of stochastic processes. The results for some important measures for system effectiveness are obtained for parametric values and costs.

II. STATE TRANSITION DIAGRAM

The following are the possible transition states of the system



The states S_0, S_1, S_2, S_3, S_4 and S_5, are regenerative while the states S_6, S_7 and S_8 are non-regenerative as shown in the transition diagram.

III. TRANSITION PROBABLILTIES

The differential transition probabilities are:

$dQ_{01}(t) = \alpha_0 e^{-(\alpha_0+\lambda)t}dt \quad dQ_{02}(t) = \lambda e^{-(\alpha_0+\lambda)t}dt \quad dQ_{15}(t) = \lambda_1 e^{-\lambda_1 t}\overline{F(t)}dt$

$dQ_{14}(t) = e^{-\lambda_1 t} f(t)dt \quad dQ_{24}(t) = e^{-\lambda_1 t} g(t)dt \quad dQ_{27}(t) = \lambda_1 e^{-\lambda_1 t}\overline{G(t)}dt$

$dQ_{51}(t) = r(t)dt \quad dQ_{62}(t) = r(t)dt \quad dQ_{73}(t) = g(t)dt$

$dQ_{38}(t) = \alpha_0 e^{-(\alpha_0+\lambda)t}\overline{R(t)}dt \quad dQ_{36}(t) = \lambda e^{-(\alpha_0+\lambda)t}\overline{R(t)}dt$

$dQ_{30}(t) = e^{-(\alpha_0+\lambda)t} r(t)dt \quad dQ_{43}(t) = \lambda_1 e^{-\lambda_1 t}dt$

$dQ_{81}(t) = r(t)dt \quad dQ_{23.7}(t) = dQ_{27}(t)©dQ_{73}(t)$

$dQ_{31.8}(t) = dQ_{38}(t)©dQ_{81}(t) \quad dQ_{32.6}(t) = dQ_{36}(t)©dQ_{62}(t)$ …(1)

By considering simple probabilistic notions, we have the following expressions for transition probabilities:

$p_{ij} = Q_{ij}(\infty) = \int_0^\infty q_{ij}(t)dt$, we have

$p_{01} = \frac{\alpha_0}{\alpha_0+\lambda}$ $p_{02} = \frac{\lambda}{\alpha_0+\lambda}$ $p_{15} = 1 - f^*(\lambda_1)$

$p_{14} = f^*(\lambda_1)$ $p_{24} = g^*(\lambda_1)$ $p_{27} = 1 - g^*(\lambda_1)$

$p_{30} = r^*(\alpha_0 + \lambda)$ $p_{23.7} = 1 - g^*(\lambda_1)$ $p_{31.8} = \frac{\alpha_0}{\alpha_0+\lambda}(1 - r^*(\alpha_0 + \lambda))$

$p_{38} = \frac{\alpha_0}{\alpha_0 + \lambda}(1 - r^*(\alpha_0 + \lambda))$ $p_{36} = \frac{\lambda}{\alpha_0 + \lambda}(1 - r^*(\alpha_0 + \lambda))$ $p_{32.6} = \frac{\lambda}{\alpha_0 + \lambda}(1 - r^*(\alpha_0 + \lambda))$

$p_{51} = p_{73} = p_{62} = p_{81} = p_{43} = 1$ …(2)

IV. MEAN SOJOURN TIMES

The MST (μ_i) is in the state S_i are

$\mu_0 = m_{01} + m_{02}$ $\mu_1 = m_{14} + m_{15}$ $\mu_2 = m_{24} + m_{27}$

$\mu_3 = m_{30} + m_{36} + m_{38}$ $\mu_4 = m_{43}$ $\mu_5 = m_{51}$

$\mu_2' = m_{24} + m_{23.7}$ $\mu_3' = m_{30} + m_{32.6} + m_{31.8}$ …(3)

V. RELIABILITY AND MEAN TIME TO SYSTEM FAILURE (MTSF)

Let $\emptyset_i(t)$ be the cdf of first passage time from regenerative state S_i to a failed state. Regarding the failed state as absorbing state, we have the following recursive relations for $\emptyset_i(t)$:

$\phi_i(t) = \sum_j Q_{i,j}(t) Ⓢ \phi_j(t) + \sum_j Q_{i,j}(t)$ …(4)

Where Sj is an un-failed regenerative state to which the given regenerative state S_i can transit and S_k is a failed state to which the state S_i can transit directly.

Taking LST of the above relations (4) and solving

we have $R^*(s) = \frac{1-\phi_S^{**}(s)}{s}$ …(5)

The reliability of the system can be obtained by taking inverse Laplace transform of (5).

The mean time to system failure (MTSF) is given by

$$MTSF = \lim_{s\to 0} \frac{1-\phi_0^{**}(s)}{s} = \frac{N_1}{D_1}$$

Where, $N_1 = \mu_0 + p_{01}\,\mu_1 + p_{02}\,\mu_2 + (\mu_3 + \mu_4)(p_{01}\,p_{14} + p_{02}\,p_{24})$ and

$D_1=1-p_{01}p_{14}\,p_{30}-p_{02}p_{24}\,p_{30}$ (6)

VI. STEADY STATE AVAILABILITY

Let $A_i(t)$ be the probability that the system is in up-state at instant 't' given that the system entered regenerative state S_i at t=0.

The recursive relations for $A_i(t)$ are given as:

$$A_i(t) = M_i(t) + \sum_j q_{i,j}^{(n)}(t)©A_j\,(t) \quad \ldots(7)$$

Where S_j is any successive regenerative state to which the regenerative state S_i can transit through n transitions $M_i(t)$ is the probability that the system is in up state initially in the state $S_i \in E$ up at time t without visiting to any other regenerative state, we have

$M_0(t) = e^{-(\alpha_0+\lambda)t}$ $M_1(t) = e^{-\lambda_1 t}\overline{F(t)}$ $M_2(t) = e^{-\lambda_1 t}\overline{G(t)}$

$M_3(t) = e^{-(\alpha_0+\lambda)t}\overline{R(t)}$ $M_4(t) = e^{-\lambda_1 t}$ …(8)

Taking LT of above relations (7) and (8) and solving for $A_0^*(s)$.

The steady state availability is given by $A_0(\infty) = \lim_{s\to 0} sA_0^*(s) = \dfrac{N_2}{D_2}$

And

$$N_2 = p_{14}p_{30}\mu_0 + \mu_1(p_{01}(1-p_{32.6}) + p_{02}p_{31.8}) + \mu_2\big(p_{01}p_{14}p_{32.6} + p_{02}p_{14}(1-p_{31.8})\big) + \mu_3 p_{14} + \mu_4(p_{01}p_{14}(1-p_{23.7}p_{32.6}) + p_{02}p_{24}(p_{24}+p_{23.7}p_{31.8}))$$

$$D_2 = p_{14}p_{30}\mu_0 + \mu_1(p_{01}p_{30} + p_{31.8}) + \mu_2' p_{14}(p_{02}p_{30} + p_{32.6}) + \mu_3' p_{14} + \mu_4 p_{14}(p_{30}(p_{01} + p_{02}p_{24}) + (p_{31.8} + p_{24}p_{32.6})) + p_{15}(1 - p_{32.6} - p_{02}p_{30})\mu_5$$

…(9)

VII. BUSY PERIOD ANALYSIS OF THE SERVER

A. BPA DUE TO REPAIR IN THE LONG RUN

Let $B^R_i(t)$ be the probability that the server is busy in repairing the main unit at an instant 't' given that the system entered regenerative state S_i at t=0.The recursive relations for $B^R_i(t)$ are as follows:

$$B_i^R(t) = W_i(t) + \sum_j q_{i,j}^{(n)}(t)©B_j^R\,(t) \quad \ldots(10)$$

where $W_i(t)$ be the probability that the server is busy in state S_i due to failure up to time t without making any transition to any other regenerative state or returning to the same via one or more non regenerative states

Where, $W_2(t) = e^{-\lambda_1 t}\overline{G(t)} + (\lambda_1 e^{-\lambda_1 t} © 1)\overline{G(t)}$ …(11)

Let us take LT of above equations (10, 11) and solving for $B_0^{R^*}(s)$.

The time for which server is busy due to repair is given by

$B_0^{R^*}(\infty) = \lim_{s\to 0} sB_0^{R^*}(s) = \frac{N_3}{D_2}$,

Where, $N_3 = W_2^*(0)(p_{01}p_{14}p_{32.6} + p_{02}p_{14}(1 - p_{31.8}))$ and D_2 is already defined …(12)

B.BPA DUE TO REPLACEMENT IN THE LONG RUN

Let $B^{Rp}_i(t)$ be the probability that the server is busy in replacement the duplicate unit at an instant 't' given that the system entered regenerative state S_i at t=0.The recursive relations for $B^{Rp}_i(t)$ are as follows:

$B_i^{Rp}(t) = W_i(t) + \sum_j q_{i,j}^{(n)}(t) © B_j^{Rp}(t)$ …(13)

where $W_i(t)$ be the probability that the server is busy in state S_i due to failure up to time t without making any transition to any other regenerative state or returning to the same via one or more non regenerative states

Where, $W_3(t) = e^{-(\alpha_0+\lambda)t}\overline{R(t)} + (\alpha_0 e^{-(\alpha_0+\lambda)t} © 1)\overline{R(t)} + (\lambda e^{-(\alpha_0+\lambda)t} © 1)\overline{R(t)}$

$W_5(t) = \overline{R(t)}$ …(14)

Let us take LT of above equations (13, 14) and solving for $B_0^{Rp^*}(s)$.

The time for which server is busy due to replacement is given by

$B_0^{Rp}(\infty) = \lim_{s\to 0} sB_0^{Rp^*}(s) = \frac{N_4}{D_2}$,

Where, $N_4 = W_3^*(0)(p_{01}p_{14} + p_{02}(1 - p_{15})) + W_5^*(0)p_{15}(p_{01}(1 - p_{32.6}) + p_{02}p_{31.8})$

And D_2 is already mentioned. …(15)

C. BPA DUE TO PREVENTIVE MAINTENANCE IN THE LONG RUN

Let $B^P_i(t)$ be the probability that the server is busy in preventive maintenance of the main unit at an instant 't' given that the system entered regenerative state S_i at t=0.The recursive relations for $B^P_i(t)$ are as follows:

$B_i^P(t) = W_i(t) + \sum_j q_{i,j}^{(n)}(t) © B_j^P(t)$ …(16)

where $W_i(t)$ be the probability that the server is busy in state S_i due to failure up to time t without making any transition to any other regenerative state or returning to the same via one or more non regenerative states

Where, $W_1(t) = e^{-\lambda_1 t}\overline{F(t)}$ …(17)

Let us take LT of above equations (16, 17) and solving for $B_0^{P^*}(s)$.

The time for which server is busy due to preventive maintenance is given by

$$B_0^P(\infty) = \lim_{s\to 0} sB_0^{P^*}(s) = \frac{N_5}{D_2}$$

Where, $N_5 = W_1^*(0)(p_{01}(1 - p_{32.6}) + p_{02}p_{31.8})$

and D_2 is already mentioned. …(18)

VIII. EXPECTED NUMBER OF VISITS BY THE SERVER

A. DUE TO REPAIR OF MAIN UNIT

Let $R_i(t)$ be the expected number of visits by the server in (0,t] to do repair of main unit given that the system entered the regenerative state S_i at t=0. The recursive relations for $R_i(t)$ are given as

$$R_i(t) = \sum_j Q_{i,j}^{(n)}(t) \circledS [\delta_j + R_j(t)]$$

…(19)

Where S_j is any regenerative state to which the given regenerative state S_j transits and $\delta_j = 1$, if S_j is the regenerative state where server does the job afresh, otherwise δ_j=0.

Let us take LST of above equations (19) and solving for $R_0^{**}(s)$.

The ENR per unit time by the server is given by

$$R_0(\infty) = \lim_{s\to 0} sR_0^{**}(s) = \frac{N_6}{D_2}$$

Where, $N_6 = p_{01}p_{14}p_{32.6} + p_{02}p_{14}(1 - p_{31.8})$ and D_2 is already mentioned

…(20)

B.DUE TO REPLACEMENT OF DUPLICATE UNIT

Let $R_{pi}(t)$ be the expected number of visits by the server in (0,t] to do replacement of duplicate unit given that the system entered the regenerative state S_i at t=0. The recursive relations for $R_{pi}(t)$ are given as

$R_{pi}(t) = \sum_j Q_{i,j}^{(n)}(t) ⓢ[\delta_j + R_{pj}(t)]$ …(21)

Where S_j is any regenerative state to which the given regenerative state S_j transits and $\delta_j = 1$, if S_j is the regenerative state where the server does the job afresh, otherwise δ_j=0.

Let us take LST of above equations (21) and solving for $R_{p_0}^{**}(s)$.

The ENRP per unit time by the server is given by

$$R_{p_0}(\infty) = \lim_{s\to 0} sR_{p_0}^{**}(s) = \frac{N_7}{D_2}$$

Where, $N_7 = p_{01} + p_{02}p_{14} + p_{15}(p_{02}p_{31.8} - p_{01}p_{32.6})$ and D_2 is already mentioned. …(22)

C. DUE TO PREVENTIVE MAINTENANCE OF MAIN UNIT

Let $P_i(t)$ be the expected number of visits by the server in (0,t] to do preventive maintenance of main unit given that the system entered the regenerative state S_i at t=0. The recursive relations for $P_i(t)$ are given as

$P_i(t) = \sum_j Q_{i,j}^{(n)}(t) ⓢ[\delta_j + P_j(t)]$ …(23)

Where S_j is any regenerative state to which the given regenerative state S_j transits and $\delta_j = 1$, if S_j is the regenerative state where the server does the job afresh, otherwise δ_j=0.

Let us take LST of above equations (23) and solving for $P_0^{**}(s)$.

The ENPM per unit time by the server is given by

$$P_0(\infty) = \lim_{s\to 0} sP_0^{**}(s) = \frac{N_8}{D_2}$$

Where, $N_8 = p_{14}(p_{01}(1 - p_{32.6}) + p_{02}p_{31.8})$ and D_2 is already mentioned. …(24)

IX. PROFIT ANALYSIS

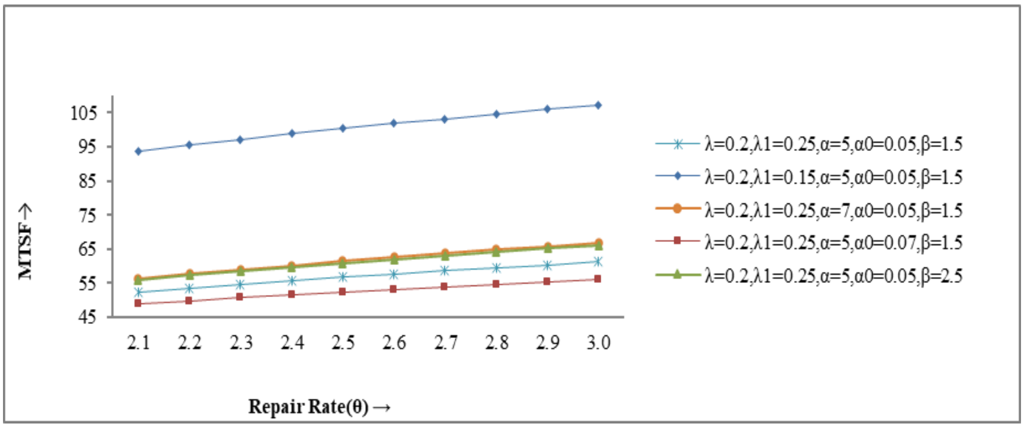
The Profit of the system model has been made by using the following expression for the profit function:

$$P = K_0A_0 - K_1B_0^R - K_2B_0^{Rp} - K_3B_0^P - K_4ER_0 - K_5ER_{P_0} - K_6EP_0$$

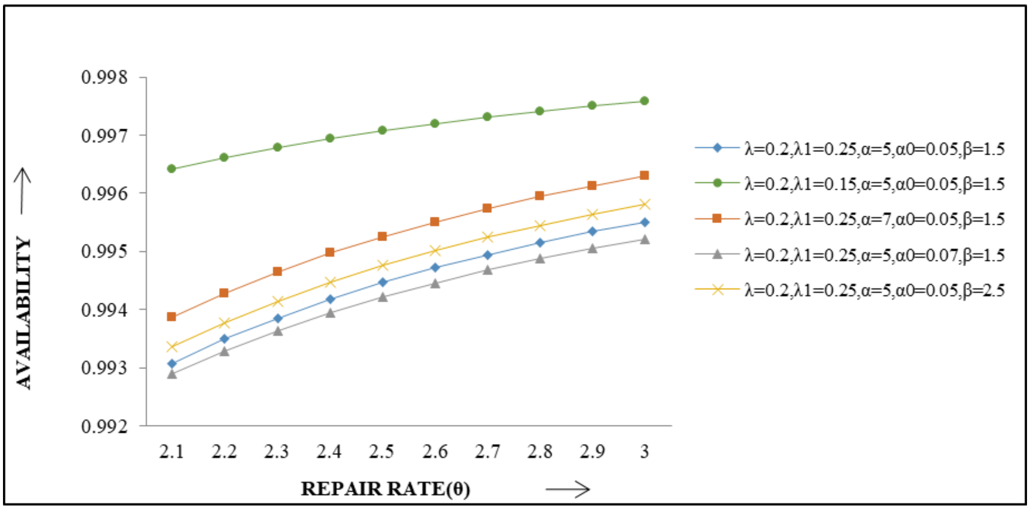
Where, the variables P, K_0 to K_6 are defined under the common notations. …(25)

X. GRAPHS

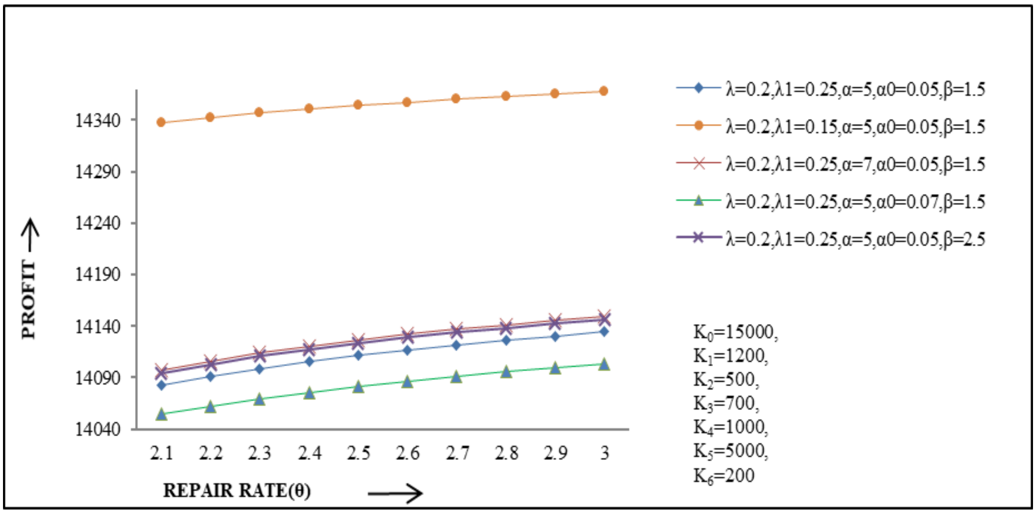
Graph 1: MTSF vs. Repair Rate (θ)



Graph 2: Availability Vs Repair Rate



Graph 3: Profit Vs Repair Rate



XI. CONCLUSION

By considering the particular case g(t)=$\theta e^{-\theta t}$, f(t) = $\beta e^{-\beta t}$and r(t)= $\alpha e^{-\alpha t}$.

Graph 1 The MTSF keep on moving up when we increase of repair rate (θ), replacement rate (α) and preventive maintenance rate (β). However, the MTSF values decline with the increase of failure rates (λ and λ_1) and the rate (α_0) by which unit undergoes for preventive maintenance.

Graph 2 indicates that availability function, in the steady state keep on decline when we increase of the rate (α0) and failure rate while there is an upward trend in their values by increasing repair rate (θ), replacement rate (α), preventive maintenance (PM) rate (β).

Graph 3 indicates that the numerical results giving particular values to the various parameters and cost are obtained to depict the behavior profit functions reveals that it is increasing by increasing repair rate (θ), replacement rate (α), preventive maintenance (PM) rate (β). However, it decreases with increase in failure rates ($\lambda.\lambda_1$) of the units and rate with which the system under goes for preventive maintenance(α_0).

Main Findings Finally, it is analyzed that the profit of the system can be improved by increasing repair rate of the main unit and replacement rate of the duplicate unit.

Note The study of Reliability Modelling and Analysis is an ongoing and evolving endeavor, and this research contributes to the body of knowledge in this field. I encourage further exploration and experimentation to refine existing models, develop new techniques, and adapt to the ever-changing landscape of technology and industry.

Through continued collaboration and innovation, we can collectively work towards a more reliable and resilient future.

XII. Notations

$E/\bar{E}$	Set of regenerative/non-regenerative states
λ / $\lambda 1$	Constant failure rate of the main unit/ duplicate unit
α_0	The rate by which main unit undergoes for preventive maintenance
α	The rate by which system undergoes for replacement
θ	The rate by which main unit undergoes for repair
β	Preventive maintenance rate of main unit
Mo/Do	Main/Duplicate unit is good and operative
DCs	Duplicate unit is in cold standby mode
MFUr /MFWr	The main failed unit is under repair/waiting for repair
DFURp/ DFWRp	The duplicate failed unit is under replacement/waiting for replacement
MPm/ MWPm	The main unit is under preventive maintenance/waiting for preventive maintenance
MFUR	The main failed unit is under repair for repair continuously from previous state
DFURP	The duplicate failed unit is under replacement continuously from previous state
MPM/ MWPM	The main unit is under preventive maintenance/ waiting for preventive maintenance continuously from previous state
g(t)/G(t)	The pdf/cdf of repair time of the main unit
f(t)/F(t)	The pdf/cdf of preventive maintenance time of the main unit
r(t)/R(t)	The pdf/cdf of replacement time of the duplicate unit
$q_{ij}(t)/Q_{ij}(t)$	The pdf /cdf of passage time from regenerative state Si to a regenerative state Sj or to a failed state Sj without visiting any other regenerative state in (0, t]
$q_{ij.kr}(t)/Q_{ij.kr}(t)$	The pdf/cdf of direct transition time from regenerative state Si to

	a regenerative state Sj or to a failed state Sj visiting state Sk, Sr once in (0, t]
$M_i(t)$	The probability that the system is up initially in regenerative state S_i at time t without visiting to any other regenerative state
$W_i(t)$	The probability that the server is busy in the state S_i upto time 't' without making any transition to any other regenerative state or returning to the same state via one or more non-regenerative states
m_{ij}	The contribution to mean sojourn time (μ_i) in state S_i when system transits directly to state S_j so that $\mu_i = \sum_j m_{ij}$ *and* $m_{ij} = \int t dQ_{ij}(t) = -q_{ij}^{*\prime}(0)$
μ_i	The mean sojourn time in state S_i which is given by $$\mu_i = E(T) = \int_0^\infty P(T > t)\, dt = \sum_j m_{ij},$$ where T denotes the time to system failure
Ⓢ/©	Symbol for Laplace-Stieltjes convolution/Laplace convolution
*/**	Symbol for Laplace Transformation /Laplace Stieltjes Transformation
$\pi_i(t)$	The cdf of first passage time from regenerative state S_i to a failed state
$A_i(t)$	The probability that the system is in up-state at instant 't' given That the system entered regenerative state S_i at t=0
$B_i^R(t)$	The probability that the server is busy in repairing the unit at an instant 't' given that system entered regenerative state S_i at t=0
$B_i^{Rp}(t)$	The probability that the server is busy in replacement the unit at an instant 't' given that system entered regenerative state Si at t=0
$B_i^P(t)$	The probability that the server is busy in preventive maintenance the unit at an instant 't' given that the system entered regenerative state Si at t=0
$R_i(t)$	The expected number of repairs by the server in (0, t] given that

	the system entered the regenerative state Si at t = 0
$R_{p_i}(t)$	The expected number of replacements by the server in (0, t] given that the system entered the regenerative state Si at t = 0
$P_i(\mathrm{t})$	The expected number of preventive maintenances by the server in (0, t] given that system entered the regenerative state S_i at t = 0

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