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Original Article

Redundancy Optimization of N+1-Unit Cold Standby System Working with a Single Operative Unit with Activation Time

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Abstract *- For every unit system, the number of cold standby units must be optimized to increase reliability and to get the maximum profit to sustain the economy and industries. Thus, a reliability model with N (a finite number) cold standby units along with a single operating unit with activation time is required to make the cold standby unit operative on need. When an operative unit fails, one of the cold standby units gets activated to become operative, functioning as effectively as the operating unit. The system is such that it needs only one working unit at a time. Computational analysis has been obtained to estimate how many standby units the system needs, cut-off points for revenue, installation costs, failure rates, activation rates, etc. The Markov process and various performability measures have been obtained using the regeneration point technique to optimize the value of N.*

Keywords *- Optimization, Redundancy, One operative unit, Cold standby units, Activation time, Regenerative point Technique, Profit analysis.*

1. Introduction

In recent years, interest in the standby concept and related challenges have grown due to increased awareness of energy use and environmental effect. To offer the system designer reliable methodology, such a trend must be sufficiently supported by procedures, mechanisms, and instruments for evaluating standby phenomena. This is especially true in reliability environments, where standby behaviours are frequently approximated or unnoticed. Enhancing system reliability and availability is the most important goal of redundancy. It is vital to enhance redundancy by installing cold standby units for a system that does not afford to shut down, fail, or even briefly suffer an interruption. Depending on the system, the cold standby unit(s) are either similar to the loaded unit or not. In the literature on reliability, many researchers have studied one, two, or three-unit cold standby redundancy systems. Various researchers investigated standby systems, assuming instantaneous start of operation of standby units on need. Murari and Goyal [8] focus on comparing profits by considering 3 models for a cold standby system with 2 units and 3 types of repair services. Goel et al. [9] investigate a cold standby system with two units where several performance metrics are assessed, and the units are subjected to repairs and correlated failures. Gupta and Goyal [12] focus on the profitability of a system consisting of 2 units that are in priority standby mode and have a delay in administrative processing while repairs are being made. Gupta and Chaudhary [13] explore a priority system with two units vulnerable to unpredictable disturbances and adhere to Rayleigh distributions of failure times. Papageorgiou and Kokolakis [10] studied a 2-unit generic parallel system consisting of n-2 cold standbys, where two units begin operating simultaneously upon the failure of n-2 cold standbys. Gopalan et al. [5,7] analyze a system having n units of cold standby and one repair facility using two approximations: dividing and grouping the state space.

Additionally, they assumed that the repair and failure times had been distributed randomly, and numerical analysis of a specific instance involving three units makes use of the normal distribution and the weibull distribution to calculate the failure time and repair time, respectively. Usha and Narayanan [14] deal with two n-cold standby systems by considering the operative unit has general-erlang failure time distribution. Yamashiro [15] studied a system that can be repaired and features N distinct failure modes along with K standby units. David [4] discussed the optimization of non-repairable systems with cold-standby redundancy.

In the literature, not much work has been reported for redundancy optimization in respect of repairable systems. However, very little such work has been done for repairable systems by some researchers, such as Batra and Taneja [1-3], who only take up to 2 standby units. Further, while dealing with an aspect of optimization of cold standby units, the consideration of activation time for making standby units operative has not been taken into account, which is required for many standby systems. The current paper establishes a reliability model to bridge such a gap.

i) Optimization of a system consisting of one operational unit and N cold standby units.
ii) Aspects of activation time required for making cold standby unit operative.
Generalized Results for the Various system effectiveness measures have been derived to optimize the anticipated use of standby units.

1.1. Assumptions of the Models

1. Initially, N units are kept on standby.
2. On failure of a unit, the cold standby is made operative for which activation time is required.
3. Activation of the standby unit, if started, is completed prior to the failed unit's repair completion.
4. The unit is restored to its original condition after repair.
5. There is only one repairman with the system.
6. The system remains operational with one operative unit.

1.2. Nomenclature

The nomenclature for various probabilities and transition densities is as follows:

λ/μ	rate of failure/ repair
β	activation rate
Cs	cold standby
CS_a	cold standby is being activated for operation.
NFr	N standby units are failed
Op	operative unit
CS_N	N units are cold standby
F_r	under repair
F_{wr}	while awaiting the repair

For other notations, one may refer to [1-3].

1.3. Transition Densities and Mean Sojourn Times

Possible system states, along with transitions, are represented in Fig 1.

The states 0, 2, 4, . . ., 2N are up states and states 1,3,5. . . 2N-1 are down states, whereas the 2N+1 state is failed state.

States of the System

State 0:(op,CS_N)
State 1:(F_r,CS_a,CS_{N-1})
State 2:(op,CS_{N-1},F_r)
State 3:$(1F_{wr},F_r,CS_a,CS_{N-2})$
State 4:$(1F_{wr},F_r,op,CS_{N-2})$
State 5:$(2F_{wr},F_r,CS_a,CS_{N-3})$
State 6:$(2F_{wr},F_r,op,CS_{N-3})$
. . .
. . .
. . .
State 2N-2:$((N-2)F_{wr},F_r,op,CS_1)$
State 2N-1:$((N-1)F_{wr},F_r,CS_a)$
State 2N:$((N-1)F_{wr},op)$
State 2N+1:(NF_{wr},F_r)

the state transition densities between state i and state j are given by

$$\begin{cases} q_{2i-2,2i-1}(t) = \begin{cases} \lambda e^{-(\lambda+\mu)t}, 1<i \le N \\ \lambda e^{-\lambda t}, i=1 \end{cases} \\ q_{2i-1,2i}(t)=1; 1 \le i \le N \\ q_{2i,2i-2}(t) = \mu e^{-(\lambda+\mu)t}, 1 \le i \le N \\ q_{2N+1,2N}(t) = \mu e^{-\mu t} \end{cases} \tag{1}$$

Thus $p_{ij} = \lim_{s\to 0} q_{ij}*(s)$ are:

$$\begin{cases} p_{2i-2,2i-1} = \begin{cases} \frac{\lambda}{\lambda+\mu}; 1<i \le N \\ 1, i=1 \end{cases} \\ p_{2i-1,2i}=1; 1 \le i \le N \\ p_{2i,2i-2} = \frac{\mu}{\mu+\lambda}; 1 \le i \le N \\ p_{2N+1,2N} = 1 \end{cases} \tag{2}$$

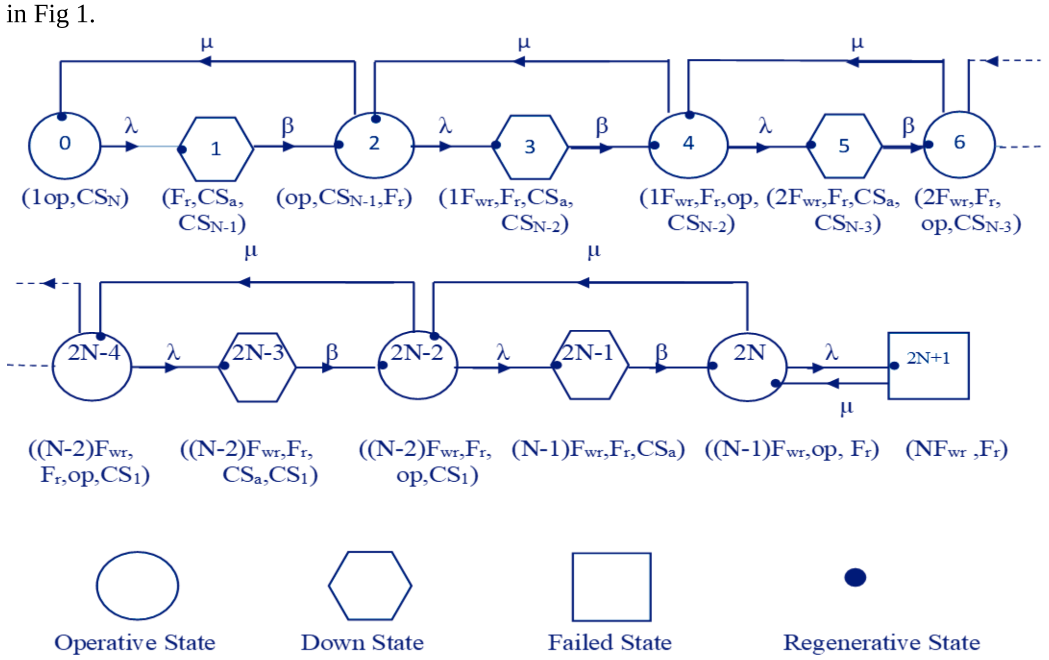

Fig.1 State transition diagram

We may, therefore, verify the following:

$$p_{2s-2,2s-1} + p_{2i,2i-2} = 1; 1 \le s \le N+1, 1 \le i \le N \quad (3)$$

Thus,

$$\begin{cases} m_{2i-2,2i-1} = \begin{cases} \int_0^\infty t\,\lambda e^{-(\lambda+\mu)t}dt = \frac{\lambda}{(\lambda+\mu)^2}; 1 < i \le N \\ \frac{1}{\lambda}, i = 0 \end{cases} \\ m_{2i-1,2i} = \frac{1}{\beta}; 1 \le i \le N \\ m_{2i,2i-2} = \frac{\mu}{(\mu+\lambda)^2}; 1 \le i \le N \\ m_{2N+1,2N} = \frac{1}{\mu} \end{cases} \quad (4)$$

Mean sojourn times (μ_i) are

$$\begin{cases} \mu_0 = \frac{1}{\lambda}, \mu_1 = \frac{1}{\beta} \\ \mu_{2i} = \int_0^\infty e^{-(\lambda+\mu)t}dt = \frac{1}{\lambda+\mu}, 1 \le i \le N \\ \mu_{2i-1} = \int_0^\infty e^{-\beta t}dt = \frac{1}{\beta}, 1 \le i \le N \\ \mu_{2N+1} = \int_0^\infty e^{-\mu t}dt = \frac{1}{\mu} \end{cases} \quad (5)$$

The sum of the unconditional mean times (m_{ij}) starting from the state, i are obtained as

$$\left.\begin{array}{l} m_{01} = \mu_0, m_{12} = \mu_1 \\ m_{2j-2,2j-1} + m_{2j,2j-2} = \mu_{2i}; 1 < j \le N+1 \ \forall\ 1 \le i \le N \\ m_{2i-1,2i} = \mu_{2i-1}; 1 \le i \le N \\ m_{2N+1,2N} = \mu_{2N+1} \end{array}\right\} \quad (6)$$

2. System Effectiveness Measurements

2.1. Mean Time to System Failure

By considering the falling state into account as an absorbing state, the following may be had:

$$\begin{cases} \phi_0(t) = Q_{01}(t)s \circ \phi_1(t) \\ \phi_1(t) = Q_{12}(t)s \circ \phi_2(t) \\ \phi_{2N-2}(t) = Q_{2N-2,2N-4}(t)s \circ \phi_{2N-4}(t) \\ \qquad + Q_{2N-2,2N-1}(t)s \circ \phi_{2N-1}(t); 2 \le i \le N \\ \phi_{2N-1}(t) = Q_{2N-1,2N}(t)s \circ \phi_{2N}(t); 2 \le i \le N \\ \phi_{2N}(t) = Q_{2N,2N-2}(t)s \circ \phi_{2N-2}(t) + Q_{2N.2N+1}(t) \end{cases} \quad (7)$$

Thus,

$$MTSF = \lim_{s\to 0} \frac{D^{(N)}(s) - N^{(N)}(s)}{sD^{(N)}(s)} = \frac{N^{(N)}}{D^{(N)}} \quad (8)$$

where

$$N^{(1)}(s) = q^*_{01}(s)q^*_{12}(s)q^*_{23}(s) \quad (9)$$

$$N^{(N)}(s) = N^{(N-1)}(s)q^*_{2N-1,2N}(s)q^*_{2N,2N+1}(s) \quad \text{for } N>1 \quad (10)$$

and

$$D^{(1)}(s) = 1 - q^*_{01}(s)q^*_{10}(s) - q^*_{01}(s)q^*_{12}(s)q^*_{20}(s) \quad (11)$$

$$D^{(2)}(s) = D^{(1)}(s) - q^*_{23}(s)q^*_{34}(s)q^*_{42}(s) \quad (12)$$

$$D^{(N)}(s) = D^{(N-1)}(s) - q^*_{2N-2,2N-1}(s)q^*_{2N-1,2N}(s)q^*_{2N,2N-2}(s)D^{(N-2)}(s) \quad \text{for } N>1 \quad (13)$$

In a steady state

$$\begin{aligned} N^{(N)} = {} & (\mu_0+\mu_1)\Big(1-\sum_{i=2}^{N} p_{2i-2,2i-1}\,p_{2i,2i-2}\Big) \\ & +\mu_2\Big(1-\sum_{i=3}^{N} p_{2i-2,2i-1}\,p_{2i,2i-2}\Big) \\ & \ldots \\ & +\mu_{2N-2}p_{23}\cdots p_{N,N-1} \\ & +(\mu_{2N-1}+\mu_{2N})p_{23}\cdots p_{2N-2,2N-1} \end{aligned} \quad (14)$$

and

$$\begin{aligned} D^{(N)} &= p_{23}p_{45}p_{67}p_{67}\cdots p_{2N,2N+1} \\ &= D^{(N-1)}p_{2N,2N+1} \end{aligned} \quad (15)$$

2.2. Availability of the System

Relational recursion includes:

$$\left.\begin{array}{l} A_0(t) = q_{01}(t)©AC_1(t) + M_0(t) \\ A_1(t) = q_{12}(t)©A_2(t) + M_1(t) \\ A_{2i-1}(t) = q_{2i-1,2i}(t)©A_{2i}(t) + M_{2i-1}(t) \\ \qquad ; 2 \le i \le N \\ A_{2i}(t) = q_{2i,2i-2}(t)©A_{2i-2}(t) \\ \qquad + q_{2i,2i+1}(t)©A_{2i+1}(t) + M_{2i}(t) \\ \qquad ; 1 \le i \le N \\ A_{2N+1}(t) = q_{2N+1,2N}(t)©A_{2N}(t) \end{array}\right\} \quad (16)$$

where

$$\left.\begin{array}{l} M_0(t) = e^{-\lambda t}, M_1(t) = e^{-\beta t} \\ M_{2i}(t) = e^{-(\mu+\lambda)t}; 1 \le i \le N \\ M_{2i-1}(t) = e^{-\beta t}; 2 \le i \le N \end{array}\right\} \quad (17)$$

The system's availability is calculated by

$$A_0 = \lim_{s\to 0} \frac{sN_1^{(N)}(s)}{D_1^{(N)}(s)} = \frac{N_1^{(N)}}{D_1^{(N)}} \quad (18)$$

where

$$\begin{aligned} D_1^{(N)} = {} & (\mu_0+\mu_1)\prod_{i=1}^{N} p_{2i,2i-2} + \mu_2 \prod_{i=2}^{N} p_{2i,2i-2} \\ & + \mu_3 p_{23}\prod_{i=2}^{N} p_{2i,2i-3} + \mu_4 p_{23}\prod_{i=2}^{N} p_{2i-3,2i-2}\,p_{2i,2i-2} \\ & +\ldots+\mu_{2N}p_{23}\prod_{i=3}^{N} p_{2i-2,2i-1} + \mu_{2N+1}p_{23}\prod_{i=2}^{N} p_{2i,2i+1} \end{aligned} \quad (19)$$

and

$$\begin{aligned} N_1^{(N)} = {} & (\mu_0+\mu_1 p_{01})\prod_{i=1}^{N} p_{2i,2i-2} \\ & + (\mu_2+\mu_3 p_{23})\prod_{i=2}^{N} p_{2i,2i-2} + \\ & \ldots \\ & + p_{23}p_{45}\ldots p_{2N-3,2N-2}p_{2N,2N-2}(\mu_{2N-2} \\ & + \mu_{2N-1}p_{2N-2,2N-1}) \\ & + p_{23}p_{45}\ldots p_{2N-2,2N-1}p_{2N-1,2N}\mu_{2N} \end{aligned} \quad (20)$$

2.3. Other Measures

2.3.1. Expected Busy Period

$$B_0 = \lim_{s \to 0} \frac{sN_2^{(N)}(s)}{D_1^{(N)}(s)} = \frac{N_2^{(N)}}{D_1^{(N)}} \quad (21)$$

2.3.2. Expected Number of Visits for Repairman

$$V_0 = \lim_{s \to 0} sV_0^{**}(s) = \lim_{s \to 0} \frac{sN_3^{(N)}(s)}{D_1^{(N)}(s)} = \frac{N_3^{(N)}}{D_1^{(N)}} \quad (22)$$

2.3.3. Expected Activation Time

$$AT_0 = \lim_{s \to 0} sAT_0^{**}(s) = \frac{N_4}{D_1} \quad (23)$$

where

$$N_2^{(N)} = \mu_1 \prod_{i=1}^{N} p_{2i,2i-2} + \mu_2 p_{12} \prod_{i=2}^{N} p_{2i,2i-2} + \ldots + p_{12}p_{23}p_{45}\ldots p_{2N-2,2N-1}p_{2N,2N-2}\mu_{2N-1} + p_{12}p_{23}p_{45}\ldots p_{2N-1,2N}\mu_{2N} + p_{12}p_{23}p_{45}\ldots p_{2N,2N+1}\mu_{2N+1} \quad (24)$$

$$N_3^{(N)} = \prod_{i=1}^{N} p_{2i,2i-2} \quad (25)$$

$$N_4^{(N)} = \mu_1 \prod_{i=1}^{N} p_{2i,2i-2} + \mu_3 p_{23} \prod_{i=2}^{N} p_{2i,2i-2} + \mu_5 p_{23} p_{45} \prod_{i=3}^{N} p_{2i,2i-2} \ldots + p_{12}p_{23}p_{45}\ldots p_{2N-2,2N-1}p_{2N,2N-2}\mu_{2N-1} + p_{12}p_{23}p_{45}\ldots p_{2N-1,2N}\mu_{2N} + p_{12}p_{23}p_{45}\ldots p_{2N,2N+1}\mu_{2N+1} \quad (26)$$

and $D_1^{(N)}$ is already defined.

3. Profit Analysis

The profit equation, therefore, is

$$\text{Profit}(P_N) = C_0AC_N - C_1B_N - C_2V_N - C_3AT_N - N.IC_0 \quad (27)$$

C_0, C_1, C_2, C_3, and IC_0 are revenue for per unit up time, cost per unit of repair time, cost per visit, the loss incurred due to per unit activation time, and cost per additional installation, respectively.

4. Numerical Results and Graphical Interpretation

- Here, the reliability measures are obtained for a system of N+1 units with arbitrary values of the parameters. The trend of the reliability measures has been shown graphically for fixed values of the parameters.

For μ=0.2, b=0.3, C_0=1500, C_1=300, C_2=100, C_3=200, IC_0=100, the numerical values and graphical presentation of MTSF are given in Figure 2

From Figure 2, it can be noted that increasing the failure rate of standby units reduces the MTSF of the system, while there is an almost linear trend when the number of standby units is increased.

- Availability Analysis when N=1,2 and 3 w.r.t λ

Table 1. MTSF of Three Models w.r.t. failure rate (λ)

Failure Rate	MTSF N=1	N=2	N=3
0.1	43.5333	118.0267	264.448
0.2	19.3833	40.6117	67.5505
0.3	13.1333	25.5467	39.328
0.4	10.3458	19.5723	29.3075
0.5	8.7813	16.4279	24.3141
0.6	7.7833	14.5017	21.3505
0.7	7.0925	13.2047	19.3955
0.8	6.5865	12.2736	18.0116
0.9	6.2	11.5733	16.9813

Table 2. Availability (N=1,2,3) w.r.t. λ

Failure Rate	Availability N=1	N=2	N=3
0.1	0.8619	0.9343	0.9662
0.2	0.6979	0.7816	0.8252
0.3	0.5763	0.6449	0.6763
0.4	0.4878	0.5410	0.5615
0.5	0.4218	0.4631	0.4766
0.6	0.3711	0.4037	0.4128
0.7	0.3310	0.3572	0.3637
0.8	0.2986	0.3201	0.3247
0.9	0.2718	0.2898	0.2933

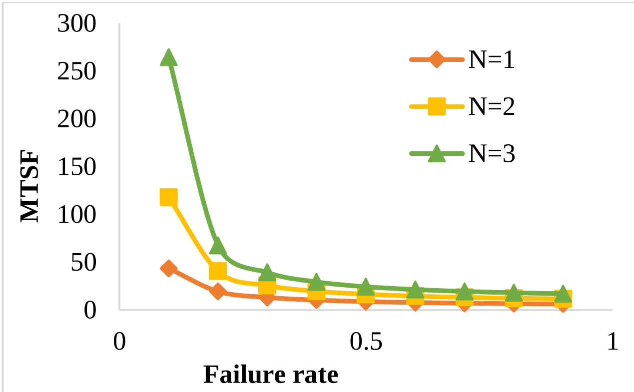

Fig. 2 Effect of Numbers of standby units on MTSF w. r. t. λ

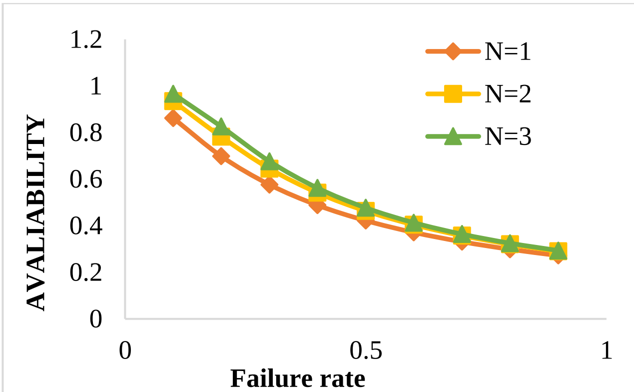

Fig. 3 Effect of Numbers of standby units on Availability w. r. t. (λ)

Figure 3 reveals that the availability has a downward trend of increasing the failure rate. However, it gets increased on increasing the number of standbys units.

- Profit Depiction for N=1,2 and 3 w.r.t λ

From Figure 4, it is found that in addition to increasing the number of standby units, the failure rate also causes a decline in profit.

- For λ=0.03, μ=0.07, β=0.03, C_1=1000, C_2=2000, C_3=1000, IC_0=2000, the following graph has been plotted as shown in Figures 5 to 7.

Table 3. Profit (N=1,2,3) w.r.t. (λ)

Failure Rate	Profit		
	N=1	N=2	N=3
0.1	961.32	954.88	896.05
0.2	618.12	623.17	577.86
0.3	386.44	371.30	310.20
0.4	225.09	190.44	115.62
0.5	107.67	58.40	-25.06
0.6	18.86	-40.96	-129.71
0.7	-50.46	-117.97	-210.03
0.8	-106	-179.21	-273.4
0.9	-151.45	-228.97	-324.61

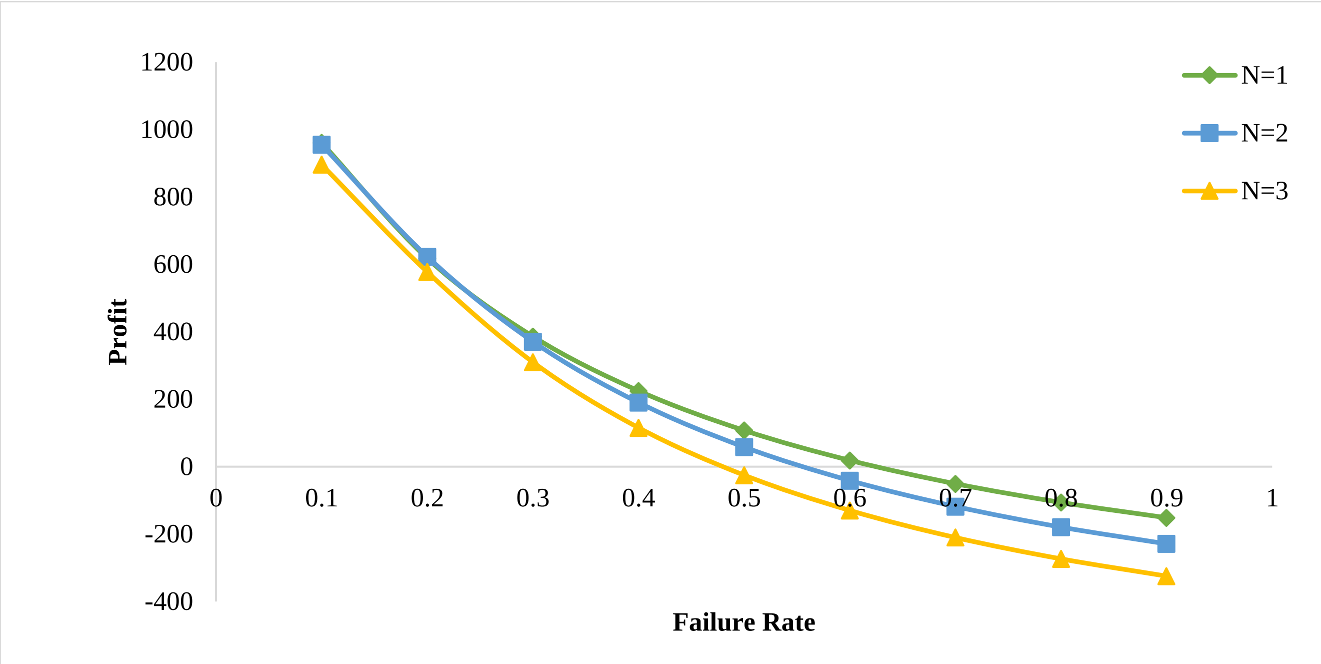

Fig. 4 Effect of numbers of standby units on profit w. r. t. λ for N=1,2,3

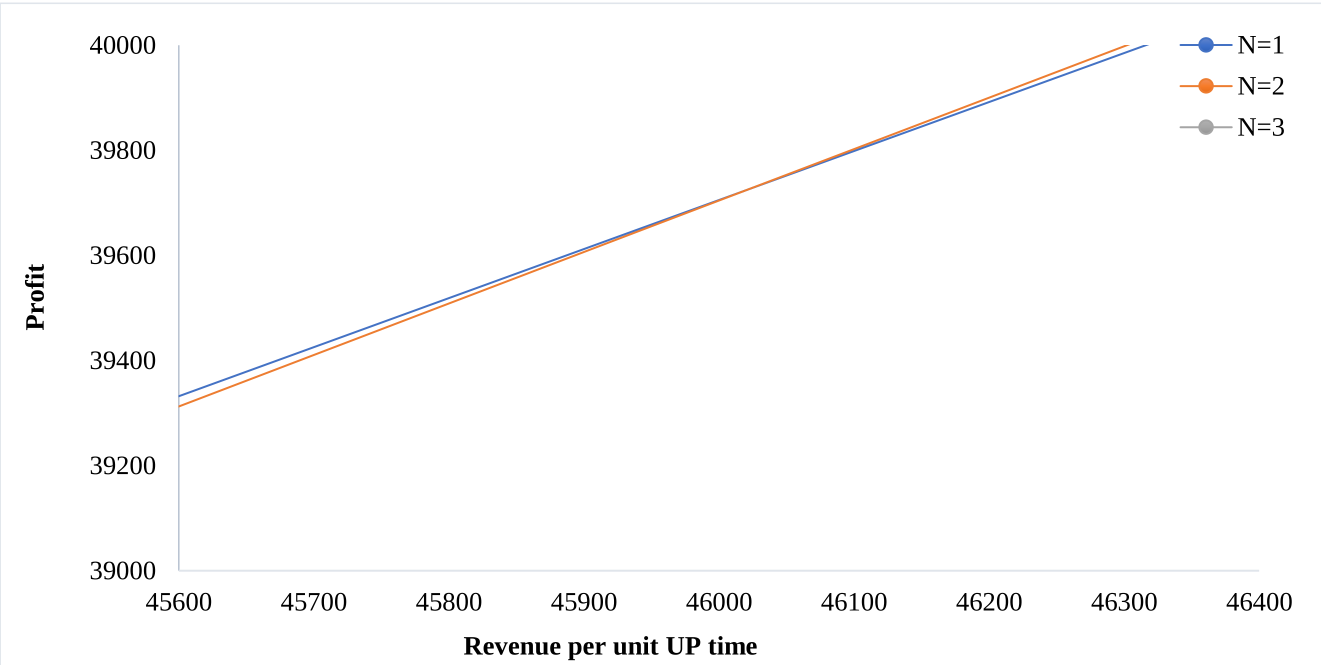

Fig. 5 Profits versus revenue (C_0) for N=1,2,3 (Keeping one standby unit)

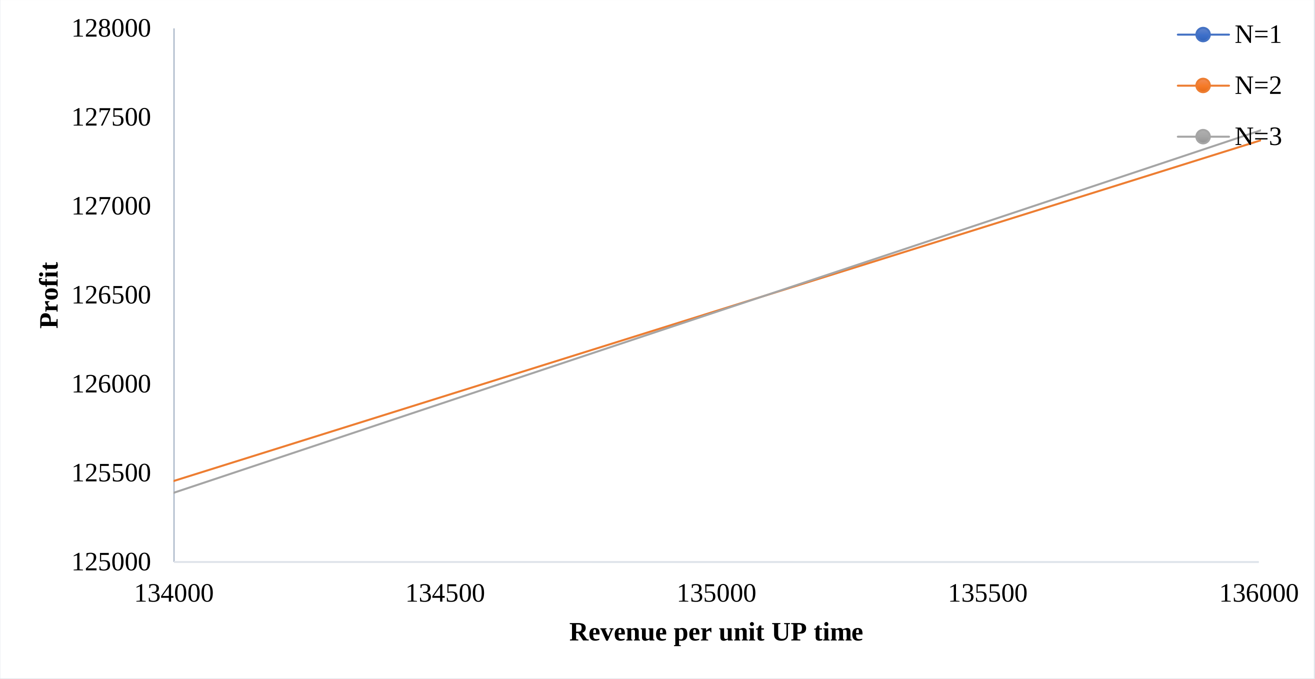

Fig. 6 Profits versus revenue (C_0) for N=1,2,3 (Keeping two standby unit)

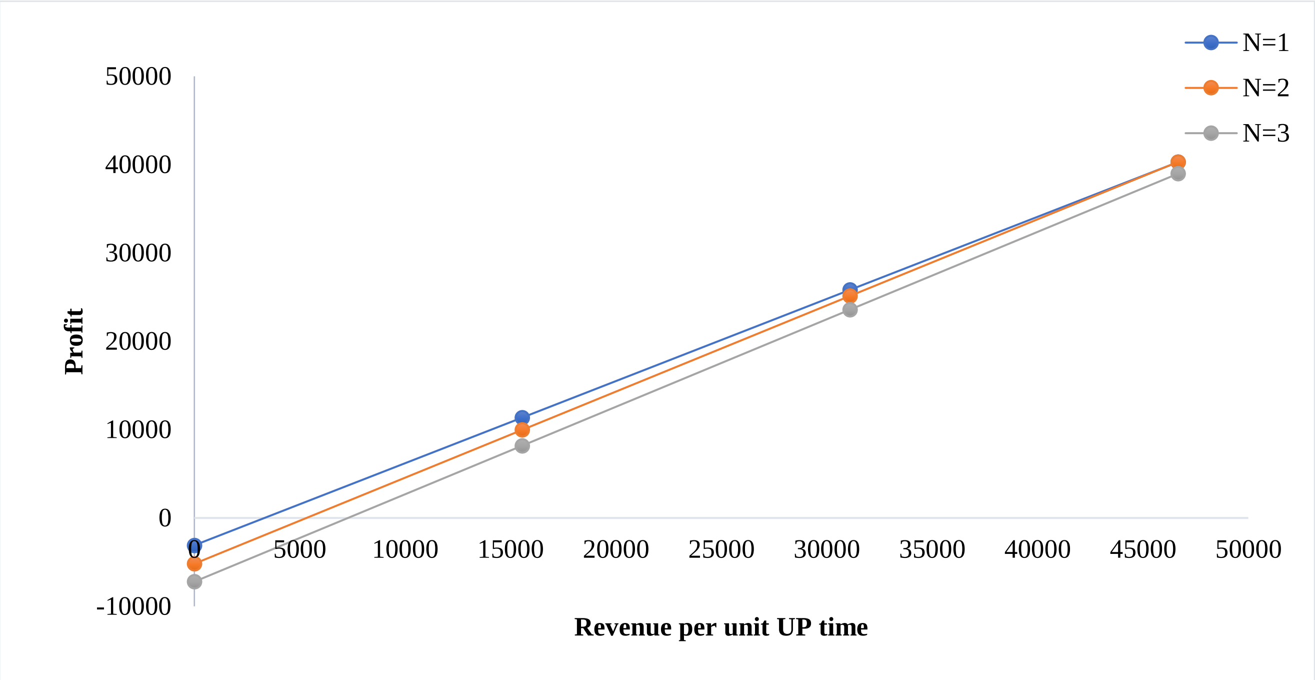

Fig. 7 Profits versus revenue (C_0) for N=1,2,3 (Keeping three standby unit)

The following may be concluded from the graphs.

- From Figure 5. we observe that when C_0 is less than 46057.23, keeping one standby unit would be profitable.
- From Figures 5 and 6, we observe that when C_0 is greater than 46057.23 but less than 135115.74, the system with two standby units is most beneficial as compared to other values of N.
- From Figure 6, we observe that when C_0 is greater than 135115.74, a system having three standby units is recommended to be used.
- From Figure 7, we conclude that the price of the items produced by the system should be fixed so that the value of C_0 is not less than 3327.22 to make the system always profitable.
- On the basis of the above, one can find how many standby units should be used and how much the price of the item to be produced should be fixed.

For λ=0.2, μ=0.5, β=0.01, C_0=2500, C_1=900, C_2=1000, and C_3=1000, the following graph has been plotted shown in Figure 8.

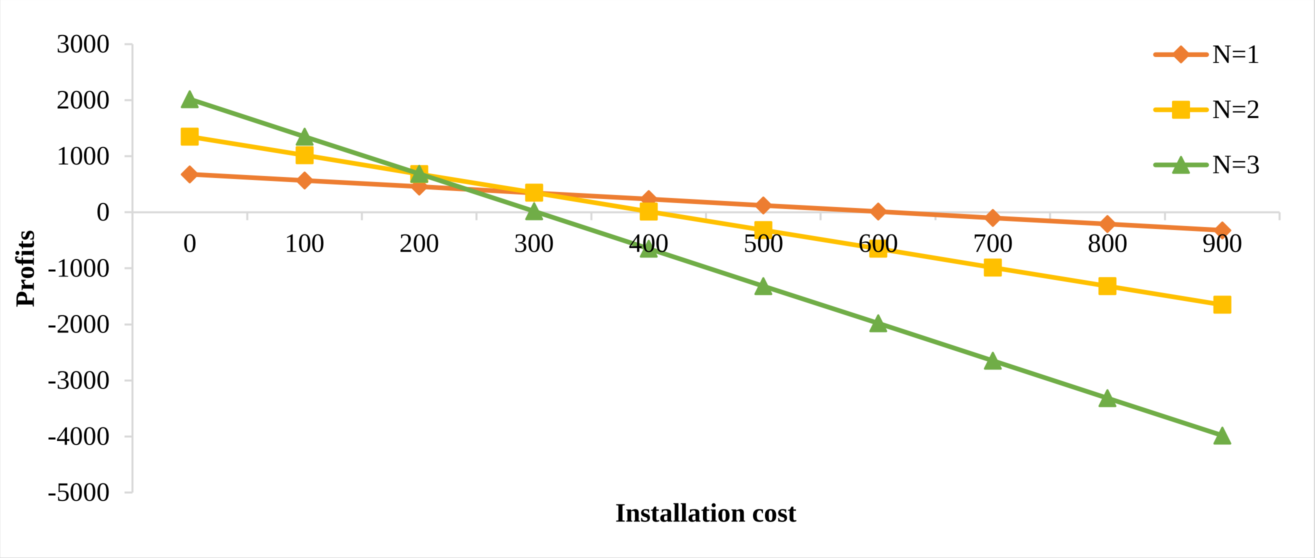

Fig. 8 Profits versus installation cost of a unit of time

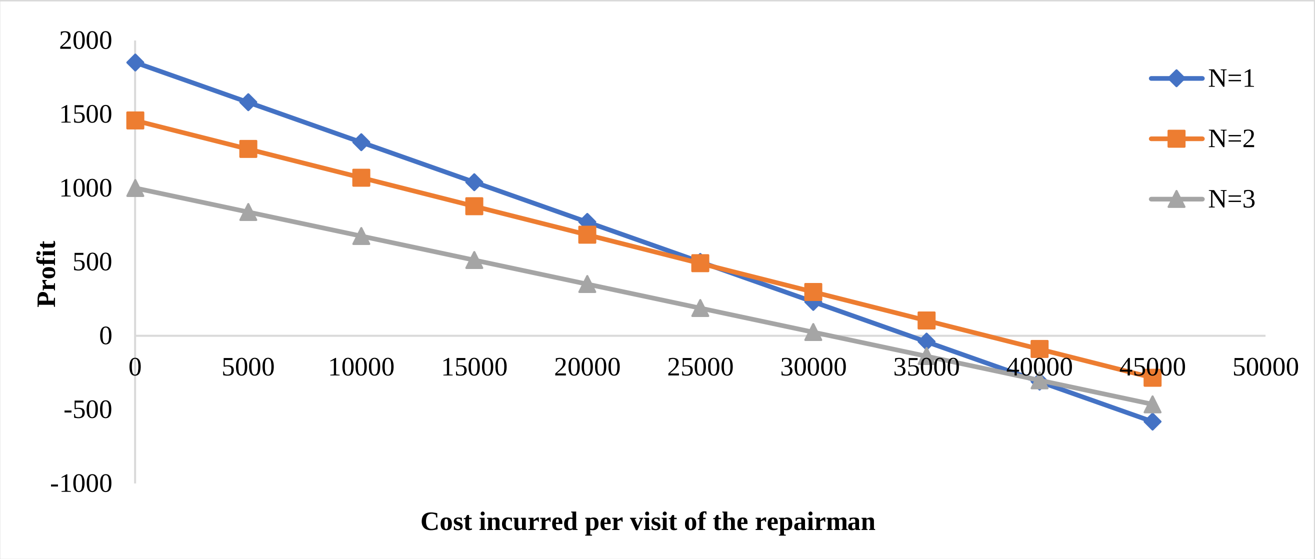

Fig. 9 Profit versus the cost incurred per visit of the repairman (C_2)

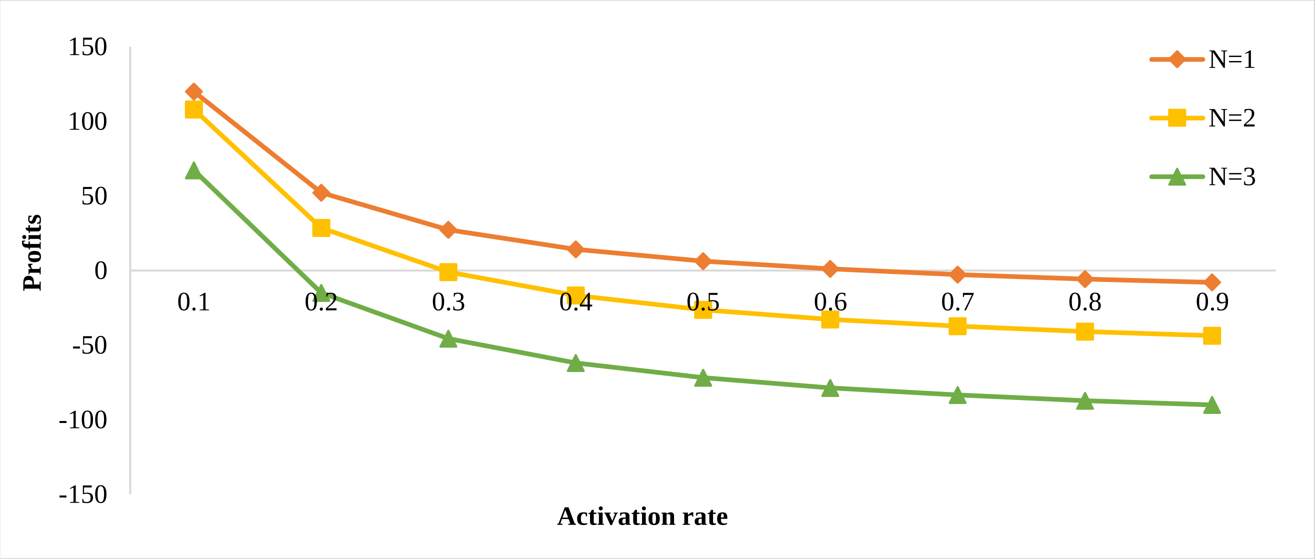

Fig. 10 Profit versus activation rate of the cold standby unit (β)

From the graph, it is recommended that:

- Three units should be taken as standby when the installation cost is less than 197.5.
- Two units should be taken as standby when the installation cost is greater than 197.5 but less than 286.32.
- One unit should be taken as a standby if the installation cost is greater than 286.32.
- The above analysis helps to decide the upper limit of the installation cost to be paid.

For λ=0.2, μ=0.3, β=0.1, C_0=5000, C_1=2000, C_3=1000, and IC_0=500, the following graph has been plotted as shown in Figure 9.

From the graph, one may recommend that:

- One unit should be taken as a standby if $C_2 < 28498.55$.
- Two and not more than two units should be taken as a standby if $C_2 > 28498.55$ for this value of C_2, as the profit becomes negative if more than 2 units are used as standby.
- Further, C_2 should not exceed 41851.85 for the system to be profitable.
- It is, therefore, recommended that the system owner should make a payment less than what is obtained at the cut-off point.

For μ=0.09, λ=0.35, C_0=1500, C_1=200, C_2=100, C_3=200, and IC_0=50, the following graph has been plotted for the profits of the three models as shown in Figure 10.

From the graph, one may observe that to have a profitable system.

- The value of β should be less than 0.694 for N=1.
- Activation rate should be less than 0.327 for N=2.
- Activation rate should be less than 0.19 for N=3.
- From the above, one can decide the value of the activation rate regarding the number of standby units to be used to have a profitable system.

5. Conclusion

This study develops a reliability model with N standby units for a system with one operational unit and considers activation time. The results match the results obtained by Batra and Taneja [1]. However, the present study is more generalized, where the value of N may also be taken as ≥ 3. In a particular case, we have represented the values of N=1,2 and 3 to determine whether we should have one, two, or more standby units for a system running with a single operating unit. The cut-off values for revenue, the installation cost per unit, the repairman's visitation cost, the activation rate, and the failure rate have been obtained. Accordingly, discussions have been made to get the optimum value of N.

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