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Reliability and Profit Analysis of a System with Effect of Temperature on Operation

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Abstract

The present paper deals with the study of a reliability model for a system in which operation is affected by variation in temperature. This situation was observed by the authors in a Fabric manufacturing company wherein the working of the system needs to be shut down when the atmospheric temperature rises beyond a certain limit which was 22ºC for that particular company. Present model is based on this situation. The problem of stopping the working of the system does not come in the winter for the location considered for the model. However, during summer, there is possibility when the system gets stopped due to dipping down in the temperature below a certain level. Various measures of the system effectiveness like MTSF, steady state availability, busy period, expected number of visit of the repairman, expected down time have been obtained making use regenerative point technique.

Keywords: Reliability, Industrial System, Temperature, Effect on Temperature and Regenerative Point Technique

INTRODUCTION

The qualitative and quantitative performance measurement of a component or a machine can be measured by reliability modeling. Concept of reliability contains a rich blend of basic and practical problems from the real world. The main aim of reliability modeling is optimization of available resources under all possible system performances including the economic forecasting of the profit. A ream of probe effort has been done on reliability modeling of systems considering different forms on failure and repair policies. We cannot ignore the effect of various failures such as major, minor and so on. Study of reliability furnishes lot of work on the reliability and cost benefit analysis of various systems. These studies are done by various researches. Lam (1995) calculated the rate of occurrence of failures for continuous time Markov chains with application to a two-component parallel system.

Gupta et al. (1996) introduced a two-unit system with correlated failures and repairs, and random appearance and disappearance of repairman. Parasher and Taneja (2007) described reliability and profit evaluation of standby system based on a master-slave concept and two types of repair facilities. Some researches such as Sims et al. (2006), Rizwan et al. (2010) and Kumar et al. (2012) defined different types of failure, i.e. wear out, random and other. Singh and Taneja (2014) carried out reliability and cost- benefit analysis of a power plant comprising two gas and one steam turbines with scheduled inspection. Manoch and Taneja (2015) depict stochastic analysis of a two-unit cold standby system with arbitrary distribution for life, repair and waiting times. Kumar and Goel (2016) discussed availability and profit analysis of a two-unit cold standby system for general distribution. Suleiman K., Ali U. A., Yusuf I. et al. (2017) represented comparison between four dissimilar solar panel configurations". None of these studies considered effect of temperature on operation of systems. However, there may exist situations where operation of the system is affected with change in temperature. Such a situation was observed by the authors in a fabric manufacturing company wherein the operation of the system is stopped when the temperature is increased beyond certain limit (22ºC in the observed situation). The system starts working only if the temperature is maintained up to this threshold value. Incorporating this idea, we, in the present paper deal with a system whose working is affected with change in temperature. If the temperature rises beyond certain limit, the system becomes inoperative i.e. it goes to down state. The model has been developed considering two different seasons i.e. winter and summer. System is undertaken for repair as soon as it gets failed.

The system is analyzed by making use of regenerative point technique. The various measures of system effectiveness as mean time to system failure (MTSF), availability in summer as well as in winter separately, busy period analysis, expected down time and expected number of visits of the repairman are derived . The profit incurred to the system is also evaluated and graphical study is done. From the data / information collected; estimates of rates, costs and probabilities are obtained and these have been used to find interesting results with regards to MTSF, availability and profitability of the system.

OTHER ASSUMPTIONS FOR THE MODEL ARE:

1. Initial state is considered as the state of working in the summer.
2. All the random variables follow arbitrary distributions.
3. After each repair, the system becomes like a new one.
4. In winter, the working of the system in not affected by variation in temperature as it cannot increase beyond the required upper limit.

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NOMENCLATURE

$w_1(t)$, $W_1(t)$	p.d.f. and c.d.f. of time of changing the season from summer to winter
$w_2(t)$, $W_2(t)$	p.d.f. and c.d.f. of time changing the season from winter to summer
$h_1(t)$, $H_1(t)$	p.d.f. and c.d.f. of time for increasing the temperature beyond certain limit
f (t), F(t)	p.d.f. and c.d.f. of failure time
g (t),G(t)	p.d.f. and c.d.f. of repair time
h (t),$H_2(t)$	p.d.f and c.d.f. of time for maintaining the temperature to acceptable range
(Op)	The operative states
(Fr)	Failure state
(D)	Down state of the system
A_0	Availability
DT_0	Expected down time
B_0	Busy period analysis
V_0	Expected number of visits by the repairman
λ	Failure rate of the operative unit
$\mu_i(t)$	Probability that system up initially in regenerative state i is up at time t without passing throw any other regenerative state
©	Symbols for Laplace Convolution
Ⓢ	Symbols for Stieltjes Convolution
*	Symbols for Laplace Transforms
**	Symbols for Laplace Stieltjes Transforms
Q_{ij}	c.d.f. of first passage time from a regenerative state i to a regenerative state j without visiting any other regenerative state in (0, t]

ANALYSIS OF MODEL

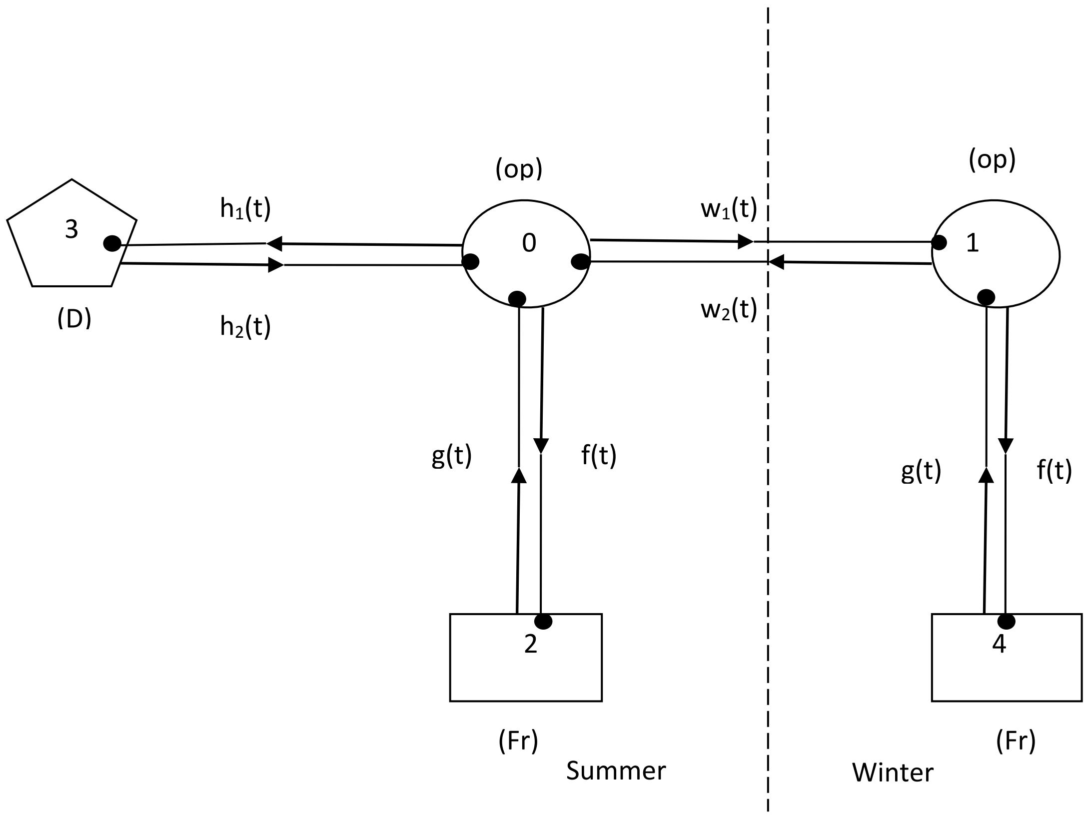

Figure 1: State Transition Diagram

Transition Probabilities and Mean Sojourn Time

The transition diagram showing various states of transition of system are shown in **Fig. 1.** The epochs of entry into the states 0, 1, 2, 3 and 4 are regenerative states. The possible transition probabilities are given below:

$$q_{01}(t) = w_1(t)\bar{H}_1(t)\bar{F}(t) \qquad q_{14}(t) = f(t)\bar{W}_2(t)$$

$$q_{02}(t) = f(t)\bar{H}_1(t)\bar{W}_1(t) \qquad q_{20}(t) = g(t)$$

$$q_{03}(t) = h_1(t)\bar{W}_1(t)\bar{F}(t) \qquad q_{30}(t) = h_2(t)$$

$$q_{10}(t) = w_2(t)\bar{F}(t) \qquad q_{41}(t) = g(t)$$

The non-zero elements p_{ij} can be obtained as $p_{ij} = \lim_{s\to\infty} q_{ij}*(s)$.

The mean sojourn times (μ_i) in the regenerative state i is defined as the time of stay in that state before transition to any other state. If T denotes the sojourn time in the regenerative state i, then

μ_i=E (T) = P_r (T>y)

$$\mu_0 = \int_0^\infty \bar{W}_1(t)\bar{H}_1(t)\bar{F}_1(t)dt = \int_0^\infty E_1(t)\,dt$$

$$\mu_1 = \int_0^\infty \bar{F}(t)\bar{W}_2(t)\,dt = \int_0^\infty E_2(t)\,dt$$

$$\mu_2 = \int_0^\infty \bar{G}(t)\,dt = -g*(o) = \int_0^\infty t\,g(t)\,dt$$

$$\mu_3 = \int_0^\infty \bar{H}_2(t)\,dt$$

$$\mu_4 = \int_0^\infty \bar{G}(t)\,dt = \mu_2$$

where

$$E_1(t) = \bar{W}_1(t)\bar{H}_1(t)\bar{F}_1(t)$$

$$E_2(t) = \bar{F}(t)\bar{W}_2(t)$$

The unconditional mean time taken by the system to transit to any regenerative state j when time is counted from the epoch of entrance into state i is mathematically stated as:

$$m_{ij} = \int_0^\infty t q_{ij}(t)\,dt = -q_{ij}^*(0) = \int_0^\infty t dQ_{ij}(t)dt$$

$$m_{01}+m_{02}+m_{03} = \int_0^\infty t\left[\begin{matrix} w_1(t)\bar{F}(t)\bar{H}_1(t) + f(t)\bar{W}_1(t)\bar{H}_1(t) \\ + h_1(t)\bar{W}_1(t)\bar{F}(t)\end{matrix}\right]dt = K_0(say)$$

$$m_{10}+m_{14} = \int_0^\infty t\left[w_2(t)\bar{F}(t) + f(t)\bar{W}_2(t)\right]dt = K_1(say)$$

$$m_{20} = \int_0^\infty t\left[g(t)\right]dt = K_2(say)$$

$$m_{30} = \int_0^\infty t\left[h_2(t)\right]dt = K_3(say)$$

$$m_{41} = K_2$$

Reliability and Mean Time to System Failure (MTSF)

Let $\phi_i(t)$ be the c.d.f. of first passage time from the regenerative state i to a failed state. Regarding the failed states as absorbing states, we have the following recursive relations for $\phi_i(t)$:

$\phi_0(t) = Q_{01}(t)$ Ⓢ $\phi_1(t)$+ $Q_{03}(t)$ Ⓢ $\phi_3(t)$+$Q_{02}(t)$

$\phi_1(t) = Q_{10}(t)$ Ⓢ $\phi_0(t)$+ $Q_{14}(t)$

$\phi_3(t) = Q_{30}(t)$ Ⓢ $\phi_0(t)$

Now taking L.S.T of equations and solving them for $\phi_0^{**}(s)$, we have

$$\phi_0^{**}(s) = \frac{N(s)}{D(s)}$$

Reliability= $L^{-1}\left[\frac{1-\phi_0^{**}(s)}{s}\right]$ and Mean Time to System Failure (MTSF) $= \lim_{s\to 0}\frac{1-\phi_0^{**}(s)}{s} = \frac{N}{D}$

where,

$$N(s) = Q_{02}^{**}(s) + Q_{01}^{**}(s)Q_{04}^{**}(s),$$

$$D(s) = 1 - Q_{01}^{**}(s)Q_{10}^{**}(s) - Q_{03}^{**}(s)Q_{30}^{**}(s)$$

$$N = K_0 + p_{01}K_1 + p_{03}\mu_3$$

$$D = p_{02} + p_{01}p_{14}$$

Availability in Summer

Let $A_i^s(t)$ be the probability that the system is in upstate at instant 't' given that the system is operative in summer and entered regenerative state i at t=0. The recursive relations for $A_i^s(t)$ are given as

$$A_0^s(t) = M_0(t) + q_{01}(t) \copyright A_1^s(t) + q_{02} \copyright A_2^s(t) + q_{03}(t) \copyright A_3^s(t)$$

$$A_1^s(t) = q_{10}(t) \copyright A_0^s(t) + q_{14} \copyright A_4^s(t)$$

$$A_2^s(t) = q_{20}(t) \copyright A_0^s(t)$$

$$A_3^s(t) = q_{30}(t) \copyright A_0^s(t)$$

$$A_4^s(t) = q_{41}(t) \copyright A_1^s(t)$$

where, $M_0(t)$ is the probability that the system is up initially in state "0" is up at time t without visiting to any other regenerative state, we have

$$M_0 = \int_0^\infty \bar{W}_1(t)\bar{H}_1(t)\bar{F}_1(t)dt = \int_0^\infty E_1(t)\,dt$$

Using Laplace transforms of and solving for, we have

$$A_0^{s*}(s) = \frac{N_1(s)}{D_1(s)}$$

and in steady state availabity in summer is given by

$$A_0^s = \lim_{s\to 0} sA_0^{s*}(s) = \frac{N_1}{D_1}$$

where,

$$N_1(s) = q_{02}^*(s) + q_{01}^*(s)q_{04}^*(s)$$

$$D_1(s) = [1 - q_{02}^*(s)q_{20}^*(s) - q_{03}^*(s)q_{30}^*(s)]$$
$$[1 - q_{14}^*(s)q_{41}^*(s)] - q_{01}^*(s)q_{10}^*(s)$$

$$D_1 = p_{10}\left(K_0 + p_{02}\mu_2 + p_{03}\mu_3\right) + p_{01}K_1$$

$$N_1 = p_{10}M_0$$

Availability in Winter

Let $A_i^w(t)$ be the probability that the system is in upstate at instant 't' given that the system is operative in winter and entered regenerative state i at t=0. The recursive relation for $A_i^w(t)$ are given as

$$A_0^w(t) = q_{01}(t) ©A_1^w(t) + q_{02} ©A_2^w(t) + q_{03}(t) ©A_3^w(t)$$

$$A_1^w(t) = M_1(t) + q_{10}(t) ©A_0^w(t) + q_{14} ©A_4^w(t)$$
$$A_2^w(t) = q_{20}(t) ©A_0^w(t)$$
$$A_3^w(t) = q_{30}(t) ©A_0^w(t)$$
$$A_4^w(t) = q_{41}(t) ©A_1^w(t)$$

Now, proceeding in the similar manner as in case of availabity in summer, we have the steady state availabity in winter as

$$A_0^w = \frac{N_2}{D_1}$$

where, $N_2 = p_{01}M_1$ and D_1 is already specified.

Other Measures of System Effectiveness

Using probabilistic arguments, the recursive relations for various measures of the system effectiveness of the system are obtained in the similar fashion as done in the preceding sections and there results have been shown below and derivations have been skipped to avoid repetition of similar derivation.

Expected Busy period (B_0) $=N_3/D_1$

Expected down time (DT_0) $= N_4/D_1$

Expected number of visits by the repairman (V_0) $=N_5/D_1$

Expected number of time the temperature is maintained whenever it reaches beyond the acceptable limit (TM_0) $=N_6/D_1$

where, $N_3 = p_{10}p_{02}W_2 + p_{01}p_{14}W_4$, $N_4 = p_{10}W_3p_{03}$, $N_5 = p_{02}p_{10} + p_{01}p_{14}$ and $N_6 = p_{03}p_{10}$

Profit Analysis

Using the measures obtained as above, the expected profit per unit time incurred to the system, in steady state, is given by

Profit $(P_0) = C_{01}A_0^s + C_{02}A_0^w - C_1(DT_0) - C_2B_0 - C_3V_0 - C_4(TM_0)$

where,

C_{01} Revenue per unit up time in summer

C_{02} Revenue per unit up time in winter

C_1 Goodwill loss per unit up time during which the system remains in down

C_2 Cost per unit time during which the repairman is engaged.

C_3 Cost per visit of the repair man

C_4 Cost per Maintenance

NUMERICAL RESULTS AND INTERPRETATION:

Following particular case is taken up to find various numerical results:

$$f(t) = \lambda e^{-\lambda t} \qquad g(t) = \alpha e^{-\alpha t}$$
$$h_1(t) = \alpha_1 e^{-\alpha_1 t} \qquad h_2(t) = \alpha_2 e^{-\alpha_2 t}$$
$$w_1(t) = \beta_1 e^{-\beta_1 t} \qquad w_2(t) = \beta_2 e^{-\beta_2 t}$$

Using the values estimated from the data collected i.e. λ=0.04167, α=0.75, α_1= 0.0455, α_2=0.75, β_1=0.00019, β_2=0.00027, C_{01}=5000, C_{02}=4000, C_1=2500, C_2=1000, C_3=1000 and C_4=500; values of various measures of system effectiveness are obtained as:

- Mean Time to System Failure (MTSF) = 25.46332443 hour
- Availability in summer (A_0^s) =0.537723
- Availability in winter (A_0^w) =0. 3783974
- Expected Busy Period (B_0) per hour =0. 0509
- Expected Fraction of Down time (DT_0) =0. 537723

- Expected number of Visits of repairman (V_0) per hour = 0. 038175
- Expected number of times per hour the temperature is maintained whenever it reaches beyond the acceptable limit (TM_0)=0.24735
- Profit incurred per hour to the system(P)=2756.454

Nature of MTSF and Availability with regard to failure rate, repair rate, etc has been noticed which reveals that:

i) MTSF decreases with increases the value of failure rate (λ) and MTSF increases with increases the values of α_1.

ii) Avalaibility in Summer decreases with increases in the values of failure rate (λ). However, it has higher values for higher values of repair rate.

iii) Avalaibility in Winter decreases with increases in the values of failure rate (λ). However, it has higher values for higher values of repair rate.

Fig. 2 depicts the behaviour of profit with respect to failure rate (λ) for different values of repair rate(α). Profit decreases with increase in the values of failure rate (λ). It has been observed that the profit increases with increase in the values of α. The change in profit for different values of λ and α is tabulated as follows:

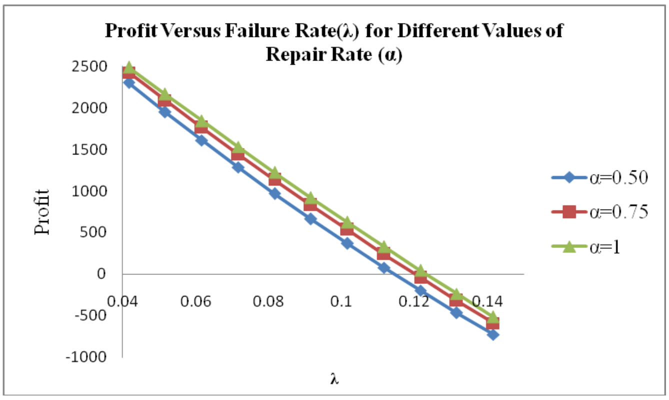

Figure 2.

The profitability aspect has been studied graphically with respect to various parameters and using the expressions for various measures of system effectiveness as shown in **Fig. 3 to 5.**

α	λ	Profit
.50	<0.11458	Negative
	>0.11458	Positive
	=0.11458	Zero
.75	< 0.12023	Negative
	>0.12023	Positive
	=0.12023	Zero
1	< 0.123277	Negative
	> 0.123277	Positive
	=0.123277	Zero

Fig.N.	Graphs	Other fixed parameter	Profit		For	Profit ≥ 0 if
			Increses	Decreases		
3	Profit versus C_{01}	C_{02}=4000, C_2=1000, C_3=1000, C_4=1000, λ= 0.04167, α=0.75	With increases in C_{01}	With increases in C_1	C_1=2400	$C_{01}\geq$1321.901
					C_1=2800	$C_{01}\geq$1721.901
					C_1=3200	$C_{01}\geq$2621.901
4	Profit versus C_{02}	C_{01}=5000, C_2=1000, C_3=1000, C_4=1000, λ= 0.04167, α=0.75	With increases in C_{02}	With increases in C_1	C_1=2400	$C_{02}\geq$1036.386
					C_1=2600	$C_{02}\geq$1178.492
					C_1=2800	$C_{02}\geq$2121.901
5	Profit versus C_1	C_{02}=4000, C_2=1000, C_3=1000, C_4=1000, λ= 0.04167, α=0.75	With increases in C_{01}	With increases in C_1	C_{01}=3000	$C_1\leq$5655.325
					C_{01}=3500	$C_1\leq$6007.177
					C_{01}=4000	$C_1\leq$6507.177

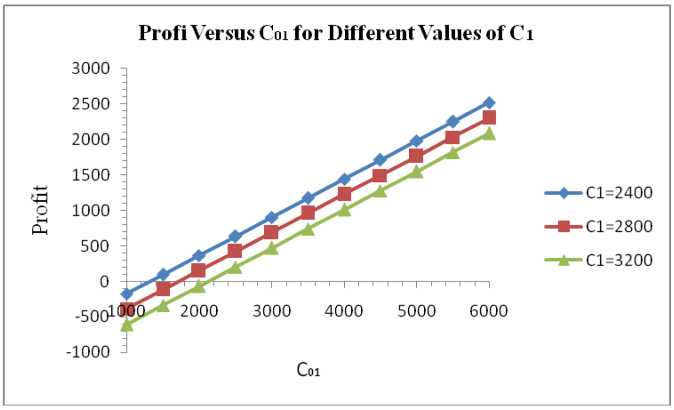

Figure 3.

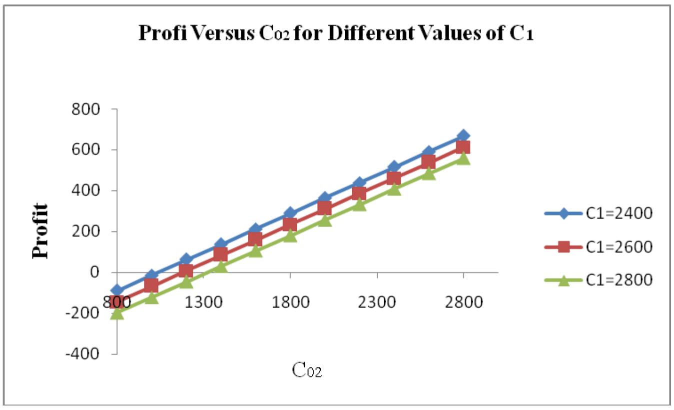

Figure 4.

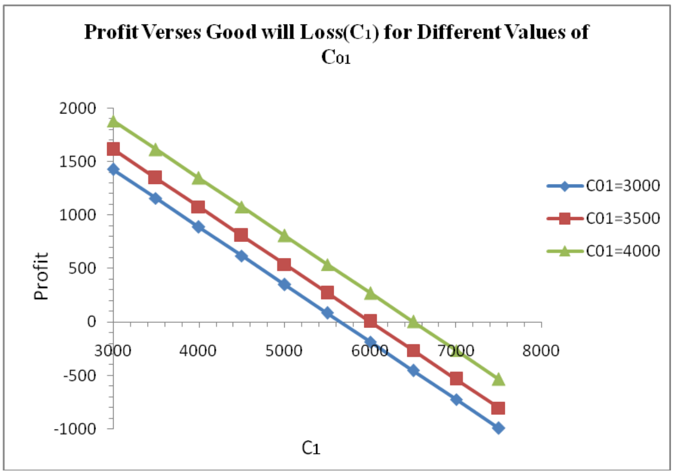

Figure 5.

However, the users of such systems may notice the effect on the measures of effectiveness with regard to parameters of interest as per their requirement and on the basis of the data available to them and then draw important conclusions regarding profitability of the system.

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