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Original Article

Stochastic analysis of a duplicated standby system subject to shocks during repair

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ABSTRACT

Two probabilistic models of a duplicated standby system subjected to random shocks during the repair are discussed. Each unit consists of mixture between hardware and software components that work together and fail independently. The first model contains regular repairman. During the repair of hardware components the regular repairman can cause a shock and damage the unit. In the second model there is an expert repairman to avoid the occurrence of shocks and to study the effect of experience level on the system. Several reliability measures for the proposed system are obtained. Finally numerical study is done to clarify the results.

1. Introduction

With tremendous progress in the industrial field, several researchers studied the probabilistic behavior of many reliability models to calculate many parameters in the reliability field. But, no attention was directed to the effect of the shocks which may be result from the repairman during the process of repairing. [1,2] studied the effect of shock on the system and divided the source of shocks into two main parts, internal factors and external source. For example stress, strain, power failure, etc. [3] studied random shocks that affect the system without reference to the reasons for their occurrence. In addition, there are many systems which contain software and hardware subsystems. [4–8] performed some studies in this area, but they are not be exposed to software subsystems. [9] developed a combined reliability model for the system that contain hardware subsystems and software subsystems. [10] discussed the probabilistic analysis of a computer system and suggested that with preventive maintenance and by giving priority to software replacement, the system will be more effective. [11] formulated reliability model of a computer system and pointed out that, in order to raise the efficiency of the system must saving hardware redundancy in cold standby. [12] concluded that by increasing the hardware repair rate and by using preventive maintenance, the system model can be more efficient and beneficial to use. This paper themes to analyze a duplicated cold standby system, each unit contains both hardware and software components that work together and fail independently. There are two models, the first contains a regular repairman who visits the system immediately when required and in case of failure due to hardware failure the repairman can cause a shock during the repair. This causing damage of the unit so it will be replaced. For example during the repair of the direct digital control panel (DDC-Panel) that control fan coil unit (FCU), the repairman may cause any short circuit or wrong connection and damage the digital output of the control module. When the failure occurred due to software failure the repairman will repair it. By replacing the regular repairman with another one which is called expert repairman as shown in the second model, the occurrence of shocks will be avoided.

The following measures of system reliability can be derived: The mean time to system failure (MTSF), Steady-state availability (SSA), Steady-state busy period due to (hardware, software and replacement) and profit analysis in the steady-state.

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2. General assumptions

1- There are 2 similar units in the system.
2- Initially one of them is operating and the other is in cold standby state.
3- The online unit faces software and hardware failures.
4- There is one repairman and always available.
5- After software failure, the repair of the unit can be performed by the repairman.
6- Failure, repair, replacement and shock times follow exponential distributions with different rates.
7- The connected switch works perfectly and instantaneously.
8- After completion of repair, the unit is as good as new.
9- The system is totally down when all its units are failed.

2.1. Assumptions for model I

1- In case of hardware failure, the regular repairman goes to repair the unit and can cause a shock during the repair of hardware failure.
2- If the regular repairman caused a shock during the repair of hardware failure then the unit will be replaced by a new one.

2.2. Assumptions for model II

1- The repairman is called an expert repairman.
2- After hardware failure, the repair of the unit can be performed by the repairman without making any shock.

3. Notations

η_1:	constant hardware failure rate.
ε_1:	constant software failure rate.
τ:	constant shock rate.
η_2:	constant hardware repair rate.
ε_2:	constant software repair rate.
ψ:	constant replacement rate.
O:	the unit is operating.
CS:	the unit is in cold standby mode.
rh:	the repair of hardware failed unit.
rs:	the repair of software failed unit.
wrh:	the hardware failed unit is waiting for repair.
wrs:	the software failed unit is waiting for repair.
repl:	unit under replacement.
$T_j(t)$:	*Pr* [the system is in state j at instant $t \geq 0$, $j = 0, 1, \cdots, n$.]
$A(t)$:	*Pr* [the system is working at instant t].
$Bh(t)$:	busy period due to hardware failure.
$Bs(t)$:	busy period due to software failure.
$Br(t)$:	busy period due to replacement.
$LFDE_s$:	linear first order differential equations.
$[\Phi_{ij}]$:	a matrix form of order 10×10.
$[\theta_{mn}]$:	a matrix form of order 4×4.
$[D_{hk}]$:	a matrix form of order 4×1.
PF:	the incurred profit of the system in the steady state.
SSBP:	steady state busy periods.
EPF:	expected total profit incurred to the system in the steady-state.
○:	Working State.
□ :	Completely Failed State.

$$T_j = \lim_{t\to\infty} T_j(t),\ \ SSA = \lim_{t\to\infty} A(t),\ \ SSBh = \lim_{t\to\infty} Bh(t),$$
$$SSBs = \lim_{t\to\infty} Bs(t),\ SSBr = \lim_{t\to\infty} Br(t)$$

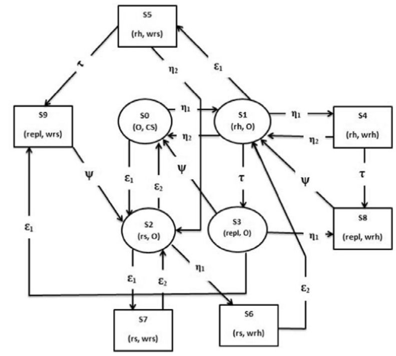

Fig. 1. Transition diagram of model I.

4. Model I

Fig. 1 shows the transition diagram of model I.
It is easy to verify that:

$$T(0) = \begin{bmatrix}1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix}. \tag{1}$$

Based on the method of $LFDE_s$ for model I the following can be obtained.

$$\left.\begin{aligned}
T_0'(t) &= -(\varepsilon_1+\eta_1)T_0(t)+\eta_2T_1(t)+\varepsilon_2T_2(t)+\psi T_3(t),\\
T_1'(t) &= -(\varepsilon_1+\eta_1+\eta_2+\tau)T_1(t)+\eta_1T_0(t)+\eta_2T_4(t)+\\
&\qquad \varepsilon_2T_6(t)+\psi T_8(t),\\
T_2'(t) &= -(\varepsilon_1+\eta_1+\varepsilon_2)T_2(t)+\varepsilon_1T_0(t)+\eta_2T_5(t)+\\
&\qquad \varepsilon_2T_7(t)+\psi T_9(t),\\
T_3'(t) &= -(\varepsilon_1+\eta_1+\psi)T_3(t)+\tau T_1(t),\\
T_4'(t) &= -(\eta_2+\tau)T_4(t)+\eta_1T_1(t),\\
T_5'(t) &= -(\eta_2+\tau)T_5(t)+\varepsilon_1T_1(t),\\
T_6'(t) &= -\varepsilon_2T_6(t)+\eta_1T_2(t),\\
T_7'(t) &= -\varepsilon_2T_7(t)+\varepsilon_1T_2(t),\\
T_8'(t) &= -\psi T_8(t)+\tau T_4(t)+\eta_1T_3(t),\\
T_9'(t) &= -\psi T_9(t)+\tau T_5(t)+\varepsilon_1T_3(t).
\end{aligned}\right\} \tag{2}$$

Eq. (2) can be put in the following matrix form:

$$T'(t) = \zeta \times T(t). \tag{3}$$

where,

$$\left(T'(t)\right)^T = \left[\ T_0'(t)\ T_1'(t)\ T_2'(t)\ T_3'(t)\ T_4'(t)\ T_5'(t)\ T_6'(t)\right.$$
$$\left.T_7'(t)\ T_8'(t)\ T_9'(t)\ \right],$$

$$(T(t))^T = [T_0(t)\ T_1(t)\ T_2(t)\ T_3(t)\ T_4(t)\ T_5(t)\ T_6(t)$$
$$T_7(t)\ T_8(t)\ T_9(t)],$$

and

$$\zeta = [\Phi_{ij}], \tag{4}$$

where,

$$\Phi_{11} = -(\varepsilon_1+\eta_1),\quad \Phi_{22} = -(\varepsilon_1+\eta_1+\eta_2+\tau),\quad \Phi_{33} = -(\varepsilon_1+\eta_1+\varepsilon_2),$$
$$\Phi_{55} = \Phi_{66} = -(\tau+\eta_2),\quad \Phi_{44} = -(\varepsilon_1+\eta_1+\psi),\quad \Phi_{13} = \Phi_{27} = \Phi_{38} = \varepsilon_2,$$
$$\Phi_{36} = \Phi_{25} = \Phi_{12} = \eta_2,\quad \Phi_{42} = \Phi_{10,6} = \Phi_{95} = \tau,\quad \Phi_{73} = \Phi_{21} = \Phi_{52} = \Phi_{94} = \eta_1,$$
$$\Phi_{31} = \Phi_{10,4} = \Phi_{83} = \Phi_{62} = \varepsilon_1,\quad \Phi_{3,10} = -\Phi_{10,10} = \psi,\quad \Phi_{14} = \Phi_{29} = -\Phi_{99} = \psi$$
$$-\Phi_{77} = -\Phi_{81} = \varepsilon_2.$$

All other elements equal to 0.
The first part in Eq. (2) can be deduced from the following:

$$T_0(t+\Delta t) = [1-(\varepsilon_1+\eta_1)\Delta t]T_0(t)+\eta_2T_1(t)\Delta t+\varepsilon_2T_2(t)\Delta t$$
$$+\psi T_3(t)\Delta t,$$

$$\frac{T_0(t+\Delta t)-T_0(t)}{\Delta t} = -(\varepsilon_1+\eta_1)T_0(t)+\eta_2 T_1(t)+\varepsilon_2 T_2(t) +\psi T_3(t),$$

as $\Delta t \longrightarrow 0$,

$$T_0'(t) = -(\varepsilon_1+\eta_1)T_0(t)+\eta_2 T_1(t)+\varepsilon_2 T_2(t)+\psi T_3(t),$$

where it can be explained according to Fig. 1 as the probability of being in state S_0 after time Δt is the probability of being operative at time t and does not move to state S_1 or state S_2 at time Δt plus the probability of being in failed state S_1 due to hardware failure at time t and being repaired at time Δt plus the probability of being in failed state S_2 due to software failure at time t and being repaired at time Δt plus the probability of being in state S_3 at time t and being replaced at time Δt.

All other parts can be explained in the same manner.

4.1. The MTSF of model I

The MTSF for model I based on $LFDE_s$ is derived.

The MTSF can be written as follows:

$$MTSF = T(0)(\delta)[D_{hk}], \tag{5}$$

where,

$$\delta = (-1)(\xi^{-1}), \qquad \xi = [\theta_{mn}],$$

$$\theta_{11} = \Phi_{11}, \quad \theta_{12} = \eta_1, \quad \theta_{13} = \varepsilon_1, \quad \theta_{21} = \eta_2, \theta_{22} = \Phi_{22},$$
$$\theta_{24} = \tau, \quad \theta_{31} = \varepsilon_2,$$
$$\theta_{33} = \Phi_{33}, \quad \theta_{41} = \psi, \quad \theta_{44} = \Phi_{44}, \quad D_{11} = 1, \quad D_{21} = 1,$$
$$D_{31} = 1, \quad D_{41} = 1.$$

All other elements equal to 0.

After simplification the MTSF is given by:

$$MTSF = \frac{\gamma_1+\gamma_2+\gamma_3+\gamma_4}{\gamma_5(\varepsilon_1^3+\gamma_6+\gamma_7+\gamma_8)}, \tag{6}$$

where,

$$\gamma_1 = \left(-\varepsilon_1\eta_1-\varepsilon_2\eta_1-\eta_1^2\right)(-\varepsilon_1-\eta_1-\psi),$$
$$\gamma_2 = \varepsilon_1\eta_1\tau+\varepsilon_2\eta_1\tau+\eta_1^2\tau,$$
$$\gamma_3 = (-\varepsilon_1-\varepsilon_2-\eta_1)(-\varepsilon_1-\eta_1-\eta_2-\tau)(-\varepsilon_1-\eta_1-\psi),$$
$$\gamma_4 = \left(\varepsilon_1\eta_1+\varepsilon_1\eta_2+\varepsilon_1\tau+\varepsilon_1^2\right)(-\varepsilon_1-\eta_1-\psi),$$
$$\gamma_5 = \varepsilon_1+\eta_1,$$
$$\gamma_6 = \eta_1(\varepsilon_2+\eta_1)(\eta_1+\tau+\psi),$$
$$\gamma_7 = \varepsilon_1^2(3\eta_1+\eta_2+\tau+\psi),$$
$$\gamma_8 = \varepsilon_1\left(\eta_1(\varepsilon_2+\eta_2+2(\tau+\psi))+\psi(\eta_2+\tau)+3\eta_1^2\right).$$

4.2. Availability analysis of model I

Upon using system of Eq. (2) with the initial condition (1) we obtain

$$T'(t) = \zeta \times T(t),$$

where, $T'(t), \zeta$ and $T(t)$ are defined in Eq. (3).

One can write Eq. (3) as

$$\zeta \times T = 0 \tag{7}$$

After solving Eq. (7), T_i's can be obtained, So

$$A = \sum_{i=0}^{3} T_i \tag{8}$$

Upon using Eq. (8) considering $\sum_{i=0}^{9} T_i=1$, we get

$$A = \frac{h_1}{h_2}, \tag{9}$$

where,

$$h_1 = \varepsilon_2\psi(\varepsilon_1+\varepsilon_2+\eta_1)(\eta_2+\tau)(\varepsilon_1+\eta_1+\eta_2+\tau)(\varepsilon_1+\eta_1+\psi),$$
$$h_2 = \sum_{i=3}^{9} h_i,$$
$$h_3 = \Gamma_2\varepsilon_1\eta_1\psi(\Gamma_2+\eta_1)(\eta_1+\psi)+\Gamma_2\varepsilon_1^4\psi,$$
$$h_4 = \varepsilon_2(\varepsilon_2+\eta_1)\left(\Gamma_2\Gamma_3\eta_1\psi+\Gamma_1\eta_1^3+\Gamma_1\Gamma_3\eta_1^2+\Gamma_2^2\psi^2\right),$$
$$h_5 = \varepsilon_1^3(\varepsilon_2(\Gamma_1\eta_1+\psi(\eta_2+\tau))+\Gamma_2\psi(\Gamma_3+3\eta_1)),$$
$$h_6 = \varepsilon_1^2\left(\Gamma_2\psi\left(\Gamma_3(\varepsilon_2+2\eta_1)+\varepsilon_2^2+3\eta_1^2\right)+\Gamma_2^2\psi^2\right),$$
$$h_7 = \varepsilon_1\varepsilon_2^2\left(\eta_1\left(2\Gamma_1\eta_1+\eta_2(\tau+2\psi)+\tau^2+3\tau\psi+\psi^2\right)+\Gamma_2\Gamma_3\psi\right),$$
$$h_8 = \varepsilon_2\varepsilon_1^2\eta_1\left(\Gamma_1(\varepsilon_2+3\eta_1)+\eta_2(\tau+3\psi)+\tau^2+4\tau\psi+\psi^2\right),$$
$$h_9 = \varepsilon_2\varepsilon_1\left(\iota+\eta_1^2(\eta_2(2\tau+3\psi)+(2\tau+\psi)(\tau+2\psi))\right),$$
$$\Gamma_1 = \tau+\psi, \Gamma_2 = \eta_2+\tau, \Gamma_3 = \eta_2+\tau+\psi, \iota = 2\Gamma_2\Gamma_3\eta_1\psi +3\Gamma_1\eta_1^3+\Gamma_2^2\psi^2.$$

4.3. The system busy period of model I

In this case, The *SSBh, SSBs*, and *SSBr* can be calculated as:

$$SSBh = (\varepsilon_2\eta_1\psi(\varepsilon_1+\varepsilon_2+\eta_1)(\varepsilon_1+\eta_1+\eta_2+\tau)(\varepsilon_1+\eta_1+\psi))/(h_2), \tag{10}$$

$$SSBs = (\varepsilon_1\psi(\varepsilon_1+\varepsilon_2+\eta_1)(\eta_2+\tau)(\varepsilon_1+\eta_1+\eta_2+\tau)(\varepsilon_1+\eta_1+\psi))/(h2), \tag{11}$$

$$SSBP = SSBh + SSBs, \tag{12}$$

and

$$SSBr = (\varepsilon_2\eta_1\tau(\varepsilon_1+\varepsilon_2+\eta_1)(\varepsilon_1+\eta_1+\eta_2+\tau)(\varepsilon_1+\eta_1+\psi))/(h2), \tag{13}$$

4.4. The profit of model I

The expected total profit per unit time incurred to the system in the steady-state is given by: Profit = total revenue - total cost

$$EPF = (C_1)SSA - (C_2)SSBh - (C_3)SSBs - (C_4)SSBr \tag{14}$$

where,

C_1: the system revenue per unit of up-time,
C_2: the cost of repair per hardware failure unit time,
C_3: the cost of repair per software failure unit time,
C_4: the cost of replacement per unit of time.

making use of Eq. (14), EPF can be given as:

$$EPF = \frac{\omega}{h_2}, \tag{15}$$

where,

$$\omega = (10\omega_1\omega_2\omega_3(\iota_1+\varepsilon_2(-\eta_1(12\tau+7\psi)+100\psi(\eta_2+\tau)))),$$
$$\iota_1 = -5\varepsilon_1\psi(\eta_2+\tau), \quad \omega_1 = \varepsilon_1+\eta_1+\psi,$$
$$\omega_2 = \varepsilon_1+\varepsilon_2+\eta_1, \quad \omega_3 = \varepsilon_1+\eta_1+\eta_2+\tau.$$

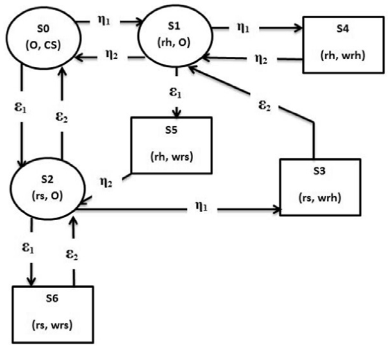

Fig. 2. Transition diagram of model II.

5. Model II

In this model the expert repairman goes to repair the failed unit due to hardware failures. There is no shock during the repair of hardware failure because of the great expertise enjoyed by the expert repairman (see Fig. 2).

The analysis of state probabilities can be obtained based on $LFDE_s$ for model II as follows:

$$\left.\begin{array}{l}
T_0^{'}(t) = -(\varepsilon_1+\eta_1)T_0(t)+\eta_2T_1(t)+\varepsilon_2T_2(t),\\
T_1^{'}(t) = -(\varepsilon_1+\eta_1+\eta_2)T_1(t)+\eta_1T_0(t)+\eta_2T_4(t)+\varepsilon_2T_3(t),\\
T_2^{'}(t) = -(\varepsilon_1+\eta_1+\varepsilon_2)T_2(t)+\varepsilon_1T_0(t)+\eta_2T_5(t)+\varepsilon_2T_6(t),\\
T_3^{'}(t) = -\varepsilon_2T_3(t)+\eta_1T_2(t),\\
T_4^{'}(t) = -\eta_2T_4(t)+\eta_1T_1(t),\\
T_5^{'}(t) = -\eta_2T_5(t)+\varepsilon_1T_1(t),\\
T_6^{'}(t) = -\varepsilon_2T_6(t)+\varepsilon_1T_2(t).
\end{array}\right\} \tag{16}$$

The first part in Eq. (16) can be deduced from the following:

$$T_0(t+\Delta t) = [1-(\varepsilon_1+\eta_1)\Delta t]T_0(t)+\eta_2T_1(t)\Delta t+\varepsilon_2T_2(t)\Delta t,$$

$$\frac{T_0(t+\Delta t)-T_0(t)}{\Delta t} = -(\varepsilon_1+\eta_1)T_0(t)+\eta_2T_1(t)+\varepsilon_2T_2(t),$$

as $\Delta t \longrightarrow 0$,

$$T_0^{'}(t) = -(\varepsilon_1+\eta_1)T_0(t)+\eta_2T_1(t)+\varepsilon_2T_2(t),$$

where it can be explained according to Fig. 2 as the probability of being in state S_0 after time Δt is the probability of being operative at time t and does not move to state S_1 or state S_2 at time Δt plus the probability of being in failed state S_1 due to hardware failure at time t and being repaired at time Δt plus the probability of being in failed state S_2 due to software failure at time t and being repaired at time Δt.

All other parts can be explained in the same manner.

5.1. The MTSF of model II

$$MTSF = \frac{\varepsilon_1(\varepsilon_2+4\eta_1+2\eta_2)+(2\eta_1+\eta_2)(\varepsilon_2+\eta_1)+2\varepsilon_1^2}{(\varepsilon_1+\eta_1)\left(\varepsilon_1(2\eta_1+\eta_2)+\eta_1(\varepsilon_2+\eta_1)+\varepsilon_1^2\right)}. \tag{17}$$

5.2. The SSA of model II

The SSA is given by:

$$\mathrm{SSA} = \frac{\varepsilon_2\eta_2(\varepsilon_1+\varepsilon_2+\eta_1)(\varepsilon_1+\eta_1+\eta_2)}{\vartheta_1+\vartheta_2+\vartheta_3}, \tag{18}$$

where,

$$\vartheta_1 = \varepsilon_1^3\eta_2+\varepsilon_2\left(\eta_1^2+\eta_2\eta_1+\eta_2^2\right)(\varepsilon_2+\eta_1),$$

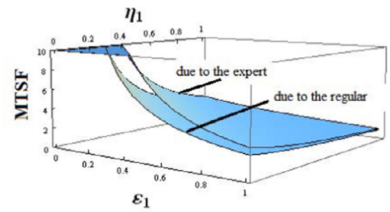

Fig. 3. variation of (MTSF) with η_1 and ε_1.

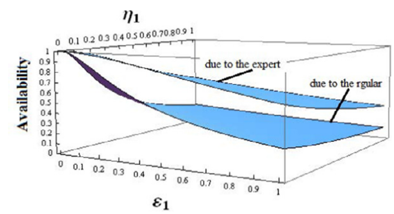

Fig. 4. variation of (SSA) with η_1 and ε_1.

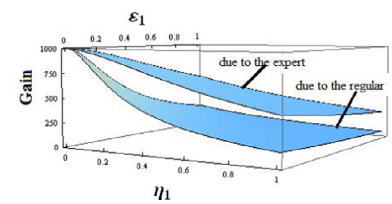

Fig. 5. variation of (EPF) with η_1 and ε_1.

$$\vartheta_2 = \varepsilon_1^2(\varepsilon_2(\eta_1+\eta_2)+\eta_2(2\eta_1+\eta_2)),$$

$$\vartheta_3 = \varepsilon_1\left(\varepsilon_2^2(\eta_1+\eta_2)+\iota_2+\eta_1\eta_2(\eta_1+\eta_2)\right),$$

$$\iota_2 = \varepsilon_2\left(2\eta_1^2+2\eta_2\eta_1+\eta_2^2\right).$$

5.3. The SSBP of model II

The SSBP is given by:

$$SSBh = (\varepsilon_2\eta_1^2\mu_1+\varepsilon_1\varepsilon_2\eta_1\mu_1+\varepsilon_2\eta_2\eta_1\mu_1)/(\vartheta_1+\vartheta_2+\vartheta_3), \tag{19}$$

$$SSBs = (\varepsilon_1^2\eta_2\mu_2+\varepsilon_2\varepsilon_1\eta_2\mu_2+\varepsilon_1\eta_1\eta_2\mu_2)/(\vartheta_1+\vartheta_2+\vartheta_3). \tag{20}$$

where,

$$\mu_1 = \varepsilon_1+\varepsilon_2+\eta_1 \& \mu_2 = \varepsilon_1+\eta_1+\eta_2.$$

5.4. The EPF of model II

The EPF is given by:

$$EPF = \frac{10(\varepsilon_1+\varepsilon_2+\eta_1)(\varepsilon_1+\eta_1+\eta_2)(10\varepsilon_2(10\eta_2-\eta_1)-7\varepsilon_1\eta_2)}{\nu 1+\nu 2+\nu 3}. \tag{21}$$

6. Numerical computation

By setting $C_1 = 1000$; $C_2 = 70$; $C_3 = 50$ and $C_4 = 120$; in case of regular repairman and by setting $C_2 = 100$ and $C_3 = 70$ in case of expert repairman, Figs. (3–6) display the variation of the MTSF, SSA, EPF and SSBP respectively for different values of η_2, ε_2, τ and ψ. where ($\eta_2 = 0.22$, $\varepsilon_2 = 0.3$, $\tau = 0.001$ and $\psi = 0.9$).

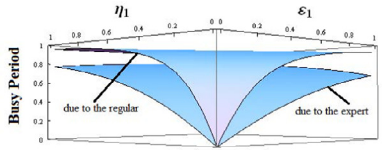

Fig. 6. variation of (SSBP) with η_1 and ε_1.

7. Conclusion

In the present paper, some measures of the system reliability such as, the MTSF, the SSA, the SSBP and the EPF are calculated using linear differential equations.

Figs. (3–6) show that:

1- The MTSF, SSA and EPF are increasing as η_1 decreasing.
2- By decreasing of ε_1, The MTSF, SSA and EPF are increasing.
3- SSBP increase with increasing η_1 and decreasing with increasing of η_2.
4- SSBP increase with increasing ε_1 and decreasing with increasing of ε_2.
5- SSBr increase with increasing τ and decreasing with increasing of ψ.
6- The MTSF, SSA and EPF in case of expert repairman is greater than it in case of regular repairman.
7- The busy period in case of regular repairman is greater than it in case of expert repairman.
8- Depending on the results obtained it is deduced that by increasing the repair and replacement rates of the unit and by replacing the regular repairman by an expert repairman, the system model can be more efficient and beneficial to use.

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