Pardeep KUMAR, Amit KUMAR
Lovely Professional University, Punjab India

RELIABILITY ANALYSIS OF AN INDUSTRIAL SYSTEM UNDER COST-FREE WARRANTY AND SYSTEM REST POLICY

Abstract: *The aim of this paper is to analyze a system, which consists of two components, working under a cost-free warranty policy. Past literature reflects that till now the focus of researchers is those systems which work without taking rest. But here authors emphasized on an industrial system which takes rest after working for a specific amount of time. This strategy helps the system to run for a long time with less failure. After taking rest, the system starts its working again. During the mathematical modeling of the system various state of the same are critically analyzed. Reliability of the considered system has been obtained for the different combinations of failure and repair rates. Also, the various parameters which affect the system performance have been evaluated.*

Keywords: performability, mathematical modeling, rest period, Markov process, warranty policy

1. Introduction

Industries are the backbone of any country. For the development of each nation, many industries are operating round the clock. Practically, some industries operate 24*7. In these industries complex and heavy machines have been installed for the production of the product. In order to produce product, companies have to follow certain maintenance strategies to optimize their production. The engineers has to look into various aspects like the design of the product, manufacturing of the product, proper installation of the product etc. for maintain failure free operation. Besides this, consumer of the product is also aware of the market trend. Before purchasing any product buyer, first of all, compares the product with other products and checks the features of the product with other products. This attention is also paid at the time of purchasing the product that repair of this product is easily

available and spare parts of the product are easily available on less cost. Keeping all these things in mind, the manufacture of the product gives warranty on the product. This warranty is an assurance to the customer that if the product fails without performing its intended task (under specified conditions) then the manufacturer will repair or replace the product on his own expense. In this way, the warranty plays a very crucial role in the sale of any product. Here in this paper authors focused on the concept of free replacement warranty (FRW) and various aspects of the same. Under this warranty, on the failure of the product, the product is properly inspected by the repairman who checks that product is failed due to the negligence of the user or not. If the product fails due to the negligence of the user the repairman declares that the warranty is completed and all the expenses of repair are borne by the user. On the other hand, when the product fails not due to the negligence of the user then the whole expense of repair or replacement is borne by the manufacturer. Here the authors also paid attention to the working of the system. Literature shows that industries work continuously to get the maximum output. But practically, the continuous working of the machine increases the failure rate of the machine, it also badly affects the revenue of the manufacturer. In this paper, we introduce a system with two independent components. These two components work independently. After working for a random amount of time system goes for rest, after taking complete rest system restarts its working and work with full efficiency. This reduces the failure rate of the components. When any of the components fails, it goes for the inspection, where repairman properly inspects the component and checks whether the component is under warranty or not. Niwas and Garg [1] presented an industrial system with a single unit which works under the cost-free warrant policy. In this, the system goes to rest after working for a random amount of time. After taking complete rest system restarts its working with full efficiency. Alqahtani and Gupta [2] inspect the warranty of remanufactured products. They developed a methodology which reduces the manufacturer cost and increases the confidence of consumers for purchasing the remanufactured products. Ambekar and Jagtap [3] gave a model which can estimate warranty cost for the products which sold with free replacement and pro rata warranties. Chukova and Hayakawa [4] developed a model for warranty claim and to compute warranty expenses. Majid et al. [5] described the genetic algorithm and explained various applications of warranty problem in optimizing total warranty cost. Zhu et al. [6] proposed an optimization model which helps to find reliability, regular price, promotion price, length of regular sale and promotion. Minjae [7] considered a model under which preventive repair is done periodically to reduce the rate of failure. In this, a threshold limit of repair time is predefined, if repair is not performed in this threshold period then the product is replaced with new product otherwise product

is repaired in such a way that it becomes operational. Warranty related management strategies were explained by [8, 9]. System designing, manufacturing, testing, maintaining and disposing of the product was discussed by [10, 11, 12, 13]. Sagayaraj [14] presented a new systematic approach for the reliability analysis of MSS which helped to determine the expected throughput and failure free-performance operation of the system. Chan and Mo [15] analyzed lifecycle reliability and maintenance analyses of wind turbines. Historical data show a high failure rate in gearboxes which require its replacement in every 5 to 7 years. Structural damage occurs frequently as a consequence of high wind load. The author in this paper applied the concept of failure mode and effective analysis and bond graph modeling to stimulate the effect of changing maintenance strategies on the life cycle cost of wind turbines. Reliability analysis of multi-state system with three-state components and its application to wind energy was defined and given by Eryilmaz [16]. An explicit formula for the enhancement of the performance of a system (to optimal level) is obtained by taking statistical dependency of the components. The model is applied to evaluate the wind power system that consists of two wind plants in different region. An optimization problem is formulated to find the optimal number of wind turbine that must be installed in the plant by minimizing the total cost under specific power production. Santiago [17] discussed the properties of probability distributions for the lifetime of the components in a system. Yingkui and Jing [18] done a review on the methods which was used to solve multi-state system and found various prospects for the same. Niwas and Kadyan [19] analyzed a single-unit system with the concept of the multiple vacations of the repairmen. The reliability and availability characteristics of 2-out of-3 standby system under a perfect repair condition were calculated by Yusuf and Hussaini [20]. Grida et al. [21] discussed availability estimation model for a 3-out-4 cold standby system and compared it with a 6-out-8 system. Keeping in mind the above literature regarding warranty, maintenance policies, mathematical modeling, reliability parameters etc. here authors get an idea to apply the concept of warranty and reliability through an mathematical modeling and Markov process in an industrial system which consists of two identical units.

The remainder of the paper has been organized as follows: In section 2, the description of the system is given with assumptions and notations. In section 3, model analysis is given and from the transition state diagram differential equations have been obtained. In section 4, assessment of the reliability of the system is done. Finally section 5 consists of conclusion of the paper.

2. Description of the system

In this paper, the authors have paid attention to an industrial system which has two components. A single repairman is always available with the system that monitors the functioning of the system carefully. Initially, both the units are operational during the working period within the warranty period. When one component fails within the warranty period then it goes for inspection. After inspecting the component properly, if repairman declares that component has failed due to the negligence of the user then management of the system will have to bear all the cost otherwise warranty company will have to bear the cost of the failed component. The whole system goes to the rest period after working for a specific amount of time. The system starts its working after taking specified rest. In the rest period, no component can fail, but the failed component can be repaired. Both failure rate and repair rate have been taken constant. The various states of the considered system is analyzed and formed in the form of a mathematical model which also known as state transition diagram (shown in fig. 1).

2.1. Assumptions

The following assumptions have been taken into consideration for the system modeling.

- A single repairman is always available for the repair of the components.
- Repair of the failed component to the user is free of cost during the warranty period, provided the failure is not due to the carelessness of the user.
- In the rest period, no component can fail, but a failed component can be repaired.
- After repair, the component is as good as a new component and works with full efficiency.
- The repair and failure rates are considered to be constant.

2.2. State naration

S_0	Initially, both components are in working condition and the system works with full efficiency.
S_1	The system is in rest state after working for a certain amount of time.
S_2	The system is in the degraded state when its first component fails.

S_3	The system is in the degraded state and it is declared by the repairman that the component has failed due to the negligence of the user.
S_4	The system is in the degraded state. It is declared by the repairman the component has failed due to the negligence of the user and the system is in the rest period.
S_5	The system is in a degraded state and it is declared by the repairman the component has not failed due to the negligence of the user.
S_6	The system works with full efficiency when its first failed component is repaired in warranty period.
S_7	The system is in the rest in warranty period when its first component has been repaired.
S_8	The system is in a degraded state due to the failure of the first component and it is in the rest period.
S_9	The system is in a failed state when its second component also fails.
S_{10}	The system is in a failed state and it is declared by the repairman the second component has failed due to the negligence of the user.
S_{11}	The system is in a failed state. It is declared by the repairman the second component has failed due to the negligence of the user and system is in the rest period.
S_{12}	The system is in the failed state and it is declared by the repairman the second component has not failed due to the negligence of the user.
S_{13}	The system works with full efficiency when its both failed components are repaired in warranty period.
S_{14}	The system is in the rest in warranty period.
S_{15}	The system is in the rest when it is in the failed state.

2.3. Notations

The following notations are taken into considerations throughout the formulation and solution of the problem.

t / s	Time unit/Inverse Laplace variable.
$p_0(t)$	Represents the probability that at any time t , the system is in the good state.
$p_1(t)$	Represents the probability that at any time t , the system is in the rest state.
$p_2(t)$	Represents the probability that at any time t , the system is in the degraded state when its first component fails.

$p_3(t)$	Represents the probability that at any time t , the system is in a degraded state and it is declared by the repairman the component has failed due to the negligence of the user.
$p_4(t)$	Represents the probability that at any time t , the system is in a degraded state and it is declared by the repairman the component has failed due to the negligence of the user and the system is in the rest period.
$p_5(t)$	Represents the probability that at any time t , the system is in the degraded state and it is declared by the repairman the component has not failed due to the negligence of the user.
$p_6(t)$	Represents the probability that at any time t , the system works with full efficiency when its first failed component is repaired in warranty period.
$p_7(t)$	Represents the probability that at any time t , the system is in the rest in warranty period.
$p_8(t)$	Represents the probability that at any time t , the system is in the degraded state due to the failure of the first component and it is in the rest period.
$p_9(t)$	Represents the probability that at any time t , the system is in a failed state when its second component also fails.
$p_{10}(t)$	Represents the probability that at any time t , the system is in failed state and it is declared by the repairman the second component has failed due to the negligence of the user
$p_{11}(t)$	Represents the probability that at any time t , the system is in the failed state. It is declared by the repairman the second component has failed due to the negligence of the user and system is in the rest period.
$p_{12}(t)$	Represents the probability that at any time t , the system is in the failed state and it is declared by the repairman the second component has not failed due to the negligence of the user.
$p_{13}(t)$	Represents the probability that at any time t , the system works with full efficiency when its both failed component is repaired in warranty period.
$p_{14}(t)$	Represents the probability that at any time t , the system is in the rest in warranty period.
$p_{15}(t)$	Represents the probability that at any time t , the system is in the rest when it is in the failed state.
λ	The constant failure rate of the single unit.
λ_1	The simultaneous failure rate of both the components.
μ	Constant repair rate of the single unit.

μ_1	Constant repair rate of both units.
a	Transition rate with which the system goes to rest.
b	Transition rate with which the system comes back to working condition.
h	Constant inspection rate of the failed unit.
p / q	Represents warranty is completed/not completed.
$p(s)$	Represents the Laplace transformation of $p(t)$.
Indicates a good state.
Indicates a degraded state.
Indicates a failed state.

3. State transition diagram

Keeping in mind all the transition between the various states of the considered system the following state transition (fig.1) diagram is developed. It depicts the different states of the considered system.

Fig. 1. State transition diagram

3.1. Formulation of differential equations from state transition diagram

$$\left[\frac{d}{dt} + a + 2\lambda \right] p_0(t) = b p_1(t) + \mu p_3(t) + \mu_1 p_{10}(t) \quad (1)$$

$$\left[\frac{d}{dt} + b \right] p_1(t) = a p_0(t) + \mu p_4(t) + \mu_1 p_{11}(t) \quad (2)$$

$$\left[\frac{d}{dt} + h + \lambda \right] p_2(t) = 2\lambda p_0(t) \quad (3)$$

$$\left[\frac{d}{dt} + a + \mu \right] p_3(t) = ph p_2(t) + b p_4(t) \quad (4)$$

$$\left[\frac{d}{dt} + \mu + b \right] p_4(t) = a p_3(t) \quad (5)$$

$$\left[\frac{d}{dt} + \mu + a \right] p_5(t) = qh p_2(t) + \lambda p_6(t) + b p_8(t) \quad (6)$$

$$\left[\frac{d}{dt} + \lambda + a \right] p_6(t) = \mu p_5(t) + b p_7(t) \quad (7)$$

$$\left[\frac{d}{dt} + b \right] p_7(t) = a p_6(t) + \mu p_8(t) \quad (8)$$

$$\left[\frac{d}{dt} + \mu + b \right] p_8(t) = a p_5(t) \quad (9)$$

$$\left[\frac{d}{dt} + h \right] p_9(t) = \lambda p_2(t) \quad (10)$$

$$\left[\frac{d}{dt} + \mu_1 + a \right] p_{10}(t) = ph p_9(t) + b p_{11}(t) \quad (11)$$

$$\left[\frac{d}{dt} + \mu_1 + b \right] p_{11}(t) = a p_{10}(t) \quad (12)$$

$$\left[\frac{d}{dt} + \mu_1 + a \right] p_{12}(t) = \lambda_1 p_{13}(t) + b p_{15}(t) + qh p_9(t) \quad (13)$$

$$\left[\frac{d}{dt} + \lambda_1 + a \right] p_{13}(t) = \mu_1 p_{12}(t) + b p_{14}(t) \quad (14)$$

$$\left[\frac{d}{dt} + b \right] p_{14}(t) = a p_{13}(t) + \mu_1 p_{15}(t) \quad (15)$$

$$\left[\frac{d}{dt} + \mu_1 + b \right] p_{15}(t) = a p_{12}(t) \quad (16)$$

and initial conditions are

$$p_i(0) = \begin{cases} 1 & ; i = 0 \\ 0 & ; i \neq 0 \end{cases} \quad (17)$$

Taking Laplace transformation of all the equations, we get

$$[s + a + 2\lambda] p_0(s) = 1 + b p_1(s) + \mu p_3(s) + \mu_1 p_{10}(s) \quad (18)$$

$$[s + b] p_1(s) = a p_0(s) + \mu p_4(s) + \mu_1 p_{11}(s) \quad (19)$$

$$[s + h + \lambda] p_2(s) = 2\lambda p_0(s) \quad (20)$$

$$[s + a + \mu] p_3(s) = ph p_2(s) + b p_4(s) \quad (21)$$

$$[s + \mu + b] p_4(s) = a p_3(s) \quad (22)$$

$$[s + \mu + a] p_5(s) = qh p_2(s) + \lambda p_6(s) + b p_8(s) \quad (23)$$

$$[s + \lambda + a] p_6(s) = \mu p_5(s) + b p_7(s) \quad (24)$$

$$[s + b] p_7(s) = a p_6(s) + \mu p_8(s) \quad (25)$$

$$[s + \mu + b] p_8(s) = a p_5(s) \quad (26)$$

$$[s + h] p_9(s) = \lambda p_2(s) \quad (27)$$

$$[s + \mu_1 + a] p_{10}(s) = ph p_9(s) + b p_{11}(s) \quad (28)$$

$$[s + \mu_1 + b] p_{11}(s) = a p_{10}(s) \quad (29)$$

$$[s + \mu_1 + a] p_{12}(s) = \lambda_1 p_{13}(s) + b p_{15}(s) + qh p_9(s) \quad (30)$$

$$[s + \lambda_1 + a] p_{13}(s) = \mu_1 p_{12}(s) + b p_{14}(s) \quad (31)$$

$$[s + b] p_{14}(s) = a p_{13}(s) + \mu_1 p_{15}(s) \quad (32)$$

$$[s + \mu_1 + b] p_{15}(s) = a p_{12}(s) \quad (33)$$

The solution of the above set of equations gives the various state probabilities of the system as following.

$$p_0(s) = \frac{1}{(s + a + 2\lambda) - bM(s) - \mu E(s) - \mu_1 F(s)} \quad (34)$$

$$p_1(s) = M(s) p_0(s) \quad (35)$$

$$p_2(s) = N(s) p_0(s) \quad (36)$$

$$p_3(s) = E(s) p_0(s) \quad (37)$$

$$p_4(s) = O(s) E(s) p_0(s) \quad (38)$$

$$p_5(s) = \frac{C(s)}{B(s)} p_0(s) \quad (39)$$

$$p_6(s) = \frac{A(s)C(s)}{B(s)} p_0(s) \quad (40)$$

$$p_7(s) = D(s) p_0(s) \quad (41)$$

$$p_8(s) = \frac{R(s)C(s)}{B(s)} p_0(s) \quad (42)$$

$$p_9(s) = S(s) p_0(s) \quad (43)$$

$$p_{10}(s) = F(s) p_0(s) \quad (44)$$

$$p_{11}(s) = T(s) F(s) p_0(s) \quad (45)$$

$$p_{12}(s) = \frac{I(s)}{G(s)} p_0(s) \quad (46)$$

$$p_{13}(s) = \frac{H(s) I(s)}{G(s)} p_0(s) \quad (47)$$

$$p_{14}(s) = \frac{U(s) I(s)}{G(s)} p_0(s) \quad (48)$$

$$p_{15}(s) = \frac{T(s) I(s)}{G(s)} p_0(s) \quad (49)$$

Where

$$A(s) = \frac{\mu[(s+b)(s+b+\mu)+ba]}{(s+b+\mu)[(s+\lambda+a)(s+b)-ba]}$$

$$B(s) = \left[(s+\mu+a) - \lambda A(s) - \frac{ba}{s+\mu+b} \right]$$

$$C(s) = \frac{2\lambda qh}{s+\lambda+h}$$

$$D(s) = \left[\frac{a}{s+b} A(s) + \frac{\mu a}{(s+b)(s+b+\mu)} \right] \frac{C(s)}{B(s)}$$

$$E(s) = \frac{2\lambda ph(s+\mu+b)}{(s+\lambda+h)[(s+\mu+a)(s+\mu+b)-ba]}$$

$$F(s) = \frac{2\lambda^2 ph(s+\mu_1+b)}{(s+\lambda+h)(s+h)[(s+\mu_1+a)(s+\mu_1+b)-ba]}$$

$$\begin{aligned}
 G(s) &= \left[(s + \mu_1 + a) - \lambda_1 H(s) - \frac{ba}{s + \mu_1 + b} \right] \\
 H(s) &= \frac{\mu_1(s+b)(s + \mu_1 + b) + \mu_1 a b}{(s + \mu_1 + b)[(s + \lambda_1 + a)(s+b) - ba]} \\
 I(s) &= \frac{2\lambda^2 qh}{(s+h)(s+\lambda+h)} \\
 M(s) &= \frac{1}{(s+b)} \left[\frac{\mu a}{s+b+\mu} E(s) + \frac{\mu_1 a F(s)}{(s+b+\mu_1)} + a \right] \\
 R(s) &= \frac{a}{s+b+\mu} \\
 T(s) &= \frac{a}{s+b+\mu_1} \\
 U(s) &= \left[\frac{a}{s+b} H(s) + \frac{\mu_1 a}{(s+b+\mu_1)(s+b)} + a \right]
 \end{aligned}$$

Hence we obtain this relationship

$$\sum_{j=0}^{15} p_j(s) = \frac{1}{s} \quad (50)$$

It is very difficult to find the inverse Laplace of these state transition probabilities since expressions of probabilities are very complex and complicated. Therefore, authors just find the reliability of the system. Reliability of the system has been obtained taking different combination of failure and repair rate.

The up (good and degraded) and down (failed) state probability of the considered system given as (from fig. 1).

$$\begin{aligned}
 p_{up}(s) &= p_0(s) + p_1(s) + p_2(s) + p_3(s) + p_4(s) + p_5(s) + \\
 &\quad + p_6(s) + p_7(s) + p_8(s) + p_{13}(s) + p_{14}(s)
 \end{aligned} \quad (51)$$

$$p_{down}(s) = p_9(s) + p_{10}(s) + p_{11}(s) + p_{12}(s) + p_{15}(s) \quad (52)$$

4. Reliability evaluation of the system

It is the probability that a system or equipment is operational when used under stated conditions in an ideal support environment. For evaluating the reliability for the considered system put the value of various parameters as $b = 0.6$, $\lambda_1 = 0.05$, $h = 0.9$, $p = q = 0.5$, $\mu = \mu_1 = 0$ in (51). We get the expression of reliability which is a function of λ and a . taking the inverse Laplace transformation of this new equation and fix $a = 0.1$ vary λ from 0.1 to 0.3 with the step size of 0.1 we get the following table 4.1, 4.2, 4.3 and corresponding graph as fig. 2 respectively.

Table 1

Reliability of the system for $\lambda = 0.1$

Time unit (t)	Reliability $R(t)$
0	1.0000000000
1	1.0000000000
2	0.9261366400
3	0.8714180320
4	0.8465212820
5	0.8388996550
6	0.8394256150
7	0.8432583470

Table 2

Reliability of the system for $\lambda = 0.2$

Time unit (t)	Reliability $R(t)$
0	1.0000000000
1	0.9947360069
2	1.0000000000
3	0.9801073219
4	0.8892734487
5	0.7368182396
6	0.5545020171
7	0.3795646629

Table 3

Reliability of the system for $\lambda = 0.3$

Time unit (t)	Reliability $R(t)$
0	1.0000000000
1	0.9780219745
2	0.9712457419
3	0.9238154756
4	0.7957831779
5	0.6029108497
6	0.3898205409
7	0.2019382563

Fig. 2. Reliability of the system for different values of λ

Now fixing $\lambda = 0.1$ and vary $a=0.2$ to $a=0.4$ with step size 0.1 we get the following Table 4.4, 4.5, 4.6 and corresponding fig. 3 for the reliability of the considered system.

Table 4

Reliability of System for $a=0.2$

Time unit (t)	Reliability $R(t)$
0	1.0000000000
1	1.0000000000
2	0.9946729023
3	0.9946729023
4	0.9083449404
5	0.7571288983
6	0.5754577038
7	0.4101022202

Table 5

Reliability of System for $a=0.3$

Time unit (t)	Reliability $R(t)$
0	1.0000000000
1	1.0000000000
2	1.0000000000
3	1.0000000000
4	0.9419648270
5	0.8249911514
6	0.6777189510
7	0.5322932574

Table 6

Reliability of System for $a=0.4$

Time unit (t)	Reliability $R(t)$
0	1.0000000000
1	1.0000000000
2	0.9261366400
3	0.8714180320
4	0.8465212820
5	0.8388996550
6	0.8394256150
7	0.8432583470

Fig. 3. Reliability of the system for different values of a

5. Result discussion and Conclusion

In this paper, we analyzed the behavior of the system which consists of two components and work under free replacement warranty. The system rests after working for random amount of time. After taking rest system starts working again. To analyze the behavior of different parameter on the system reliability, we firstly vary failure rate λ from 0.1 to 0.3 and we get values in the first three tables. From fig. 2 it can be seen that system reliability is maximum for $\lambda = 0.2$ till $t = 4$ unit. After $t = 4$ system reliability increases for $\lambda = 0.1$. But system's reliability continuously decreases for $\lambda = 0.3$. It can be seen that with the increase in the value of λ reliability decreases. In fig.3, the system is equally reliable for $a = 0.2$ and $a = 0.3$ till the time is $t=4$. System in fig.3 becomes more reliable for $a = 0.4$ after $t = 5$. So, we see that when the rest period increased system reliability. So, we see that economically this system is beneficial and it works for long period of time.

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