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Bayesian estimate of system availability for consecutive k-out-of-n:F system

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ABSTRACT

In the efficient design and functionality of complex systems, redundancy problems in systems play a key role. The consecutive-k-out-of-n:F structure, which has broad application in street light arrangements, vacuum systems in an accelerator, sliding window detection, relay stations for a communication system. Availability is one of the significant measures for a maintained device because availability accounts for the repair capability. A very significant feature is the steady-state availability of a repairable device. For the repairable consecutive k-out-of-n:F system with independent and identically distributed components, the Bayesian point estimate (B.P.E) of steady-state availability under squared error loss function (SELF) and confidence interval are obtained.

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1. INTRODUCTION

An engineer might need to utilize his judgment and previous knowledge in practice with the help of parameters of the basic life distribution, contributing to the Bayesian reliability/availability calculation. There is a strong impetus to use previous knowledge, especially when the sample size is small. It is preferred to use the operational information on its components to defeat a problematic situation if the information on the whole device is unavailable or pricey. The parameter is viewed as a random variable in the Bayesian method, to which probability density function or probability mass function is applied depending on experience.

To achieve these reliability objectives, systems are evaluated concerning their reliability characteristics. Availability is one of the significant measures for a maintained device because availability accounts for the repair capability. A very significant feature is the steady-state availability (A_s) of a repairable system. The other terminologies used to denote A_s are the long-term availability or operational readiness. A consecutive k-out-of-n:F (denoted as cons/k-n:F) system fails whenever k components fail that too in consecutive where k ≤ n. Kuo and Zuo [1] defined that if the components of cons/k-n:F system are placed in a line, then the system is a linear consecutive k-out-of-n:F (L(cons/k-n:F)) system and if the components of the cons/k-n:F system are arranged in a circle, then the system is circular consecutive k-out-of-n:F (C(cons/k-n:F)). In the L(cons/k-n:F)first and last components are not consecutive, whereas in the C(cons/k-n:F), first and last components are consecutive.

The method of incorporating likelihood functions and prior distribution with the Bayes theorem to predict the posterior distribution helps to estimate the Bayesian availability. It is easy to interpret and utilize the proposed steps. The degree of operational readiness is estimated by Bayesian availability. In a sampling technique, the confidence interval tests the degree of error or certainty. The accuracy and sensitivity of the estimate is indicated at 95% or 99% confidence level.

The Bayesian approach depends on the prior data provided in the conditional distribution. Prior distributions are called conjugate prior when the same distribution taken as the posterior. Hamada *et al.* [2] defined that conjugate priors are preferred according to the mathematical simplicity of interpretation. Gaver and Mazumdar [3] indicated that loss functions are used to determine the error between output of our calculation and the given target value. Due to its analytical tractability and mathematical simplicity, the squared error loss function (SELF) is a commonly used symmetric loss function in Bayesian analysis. In fault-tolerance systems, the k-out-of-n structure is one of the frequently used redundancies. To our knowledge, the Bayesian point estimate (B.P.E) of steady-state availability for cons/k-n:Fsystem is not yet obtained.

In this paper, we find the B.P.E of steady-state availability for cons/k-n:Fsystem and the 95% confidence interval based on the posterior distribution for cons/k-n:Fsystem with independent and identically distributed (i.i.d.) components with constant failure and repair rate. The rest of this paper is structured as follows; the background details are presented in section 2. Section 3 gives the evaluation of the B.P.E of steady-state availability, followed by section 4 where the numerical illustrations are given and section 5 gives the conclusion.

The availability of operational system has been addressed in the literature by various researchers. Hajeeh [4] presented analytical expressions for the mean time to failure (MTTF) and steady-state availability under random and common cause failures. Jain and Gupta [5] derived the expressions for the system reliability and availability under various configuration and also discussed the transient mode which provides a system characterization to designers. For a cold standby repairable k-out-of-n system Yaghoubi *et al.* [6] derived the steady-state availability expression in a closed form.

Performance of system based on reliability availability measures are discussed [7]-[9]. Rudkovsky and Mikhailov [10] constructed an efficient algorithm to estimate steady-state availability. Ke and Chu [11] analyzed the steady-state availability for a repairable system. Sahin *et al.* [12] obtained a more productive system with the help of its performance analysis. Karthikeyan *et al.* [13] obtained the cost function for the proposed multilevel inverter based on the mean time to failure and its reliability. Kela *et al.* [14] proposed a method to optimize the reliability cost by the algorithm called Flower Pollination.

Smadi *et al.* [15] derived maximum likelihood estimators, asymptotic confidence intervals and also performed a simulation study. Sarma *et al.* [16] used an analytical approach to assess the reliability and the results are validated using simulation. Tawfiq *et al.* [17] presented the system reliability using the Markov process and block diagram technique which is helpful to achieve accurate and faster reliability. Aval and Ahadi [18] used the fault tree method to estimate the reliability of wind turbines and discussed several case studies to reveal the effectiveness of the proposed method.

Bayesian availability was first discussed by David M. Brender in the year 1968. Brender [19] predicted system reliability using Bayesian treatment. A basic model has been involved and its point availability is proved to have a beta distribution. The Bayesian evaluation findings of system availability were extended by Brender [20] under different categories. With the aid of Markov method, Gaver and Mazumdar [3] obtained Bayes' estimation of long-term availability in two-state systems.

Tillman *et al.* [21] established the Bayesian method for the study of availability problems and derived the function of availability from the equation of renewal theory. Gamma priors and the Bayes theorem were used by Kuo [22] to derive steady-state availability and instantaneous availability. By assuming prior distribution for both failure time and repair time distributions, Sharma and Bhutani [23] acquired Bayes point estimator for system availability and its confidence interval. For series and parallel systems, Thompson *et al.* [24] computed Bayes confidence intervals for the availability.

For a k-out-of-m system, Islam and Khan [25] used geometric failure and repair time distribution to estimate the Bayesian point and availability. Khan and Islam [26] studied various Bayesian point estimateswith half-normal lifetime. Vásquez *et al.* [27] presented the Bayesian method of estimating the limiting availability of a one-unit device and also used the maximum likelihood method Madhumitha and Vijayalakshmi [28] estimated the Bayesian reliability for the cons/k-n:F system.

An exact expression for system reliability and availability was obtained by Griffith and Govindarajulu [29]. First they derived the system reliability expression for consecutive k-out-of-n:F system using Markov chain technique. Next, they extended their result to availability models. Further, they proved a result that "If there are no queues of failed components waiting for the operation, then the relationship between the availability of the steady-state system and the availability of steady-state components is the same as the relationship between system reliability and the reliability of components".

2. BACKGROUND

2.1. Notations

μ_1 – Component failure rate
μ_2 – Component repair rate
MTBF – Mean time between failure
MTTR – Mean time to repair
T – Total testing time
r_1 - Number of failures in $(0, T)$
r_2 - Number of repairs in $(0, T)$
p.d.f. – probability density function
p.m.f. – probability mass function
$G(u, v)$ - gamma distribution with scale parameter v and shape parameter u
$B(a, b)$ - Beta function
A_c - Component steady-state availability
A_s – System steady-state availability
A_{ss} - A_s of a series system
A_{sp} - A_s of a parallel system
A_s^L- Steady-state availability of L(cons/k-n:F)
A_s^C- Steady-state availability of C(cons/k-n:F)
A_s^{L*} - B.P.E for steady-state availability of L(cons/k-n:F)
A_s^{C*}- B.P.E for steady-state availability of C(cons/k-n:F)
A_{ss}^*- B.P.E for A_s of series system
A_{sp}^*- B.P.E for A_s of parallel system

2.2. Assumptions

- All components are good and operating at time $t = 0$
- A component has only two states, working state or failed state.
- Components are independent and identically distributed (i.i.d.).
- The time to failure and time to repair of each component are exponentially distributed.
- There is only one repairman. When a component fails, repair immediately commences.
- The repair is carried out in a first come first serve basis.
- The repaired component is as good as new.
- The probability of two or more components being returned to working conditions or failing in a short period of time is negligible.
- The system fails whenever k consecutive components fail where $k \leq n$

Let the failure time X of each component be distributed as exponential with p.d.f

$$f(x) = \mu_1 e^{-\mu_1 x}\ ,\ x,\ \mu_1 > 0 \tag{1}$$

where μ_1–component failure rate, and $\frac{1}{\mu_1}$ – MTBF

Let the repair time Y of each component be distributed as exponential with p.d.f

$$f(y) = \mu_2 e^{-\mu_2 y}\ ,\ y,\ \mu_2 > 0 \tag{2}$$

where μ_2–component repair rate, and $\frac{1}{\mu_2}$– MTTR

The steady-state component availability A_c is defined as the ratio of MTBF to MTBF+MTTR

$$A_c = \frac{\mu_2}{\mu_2+\mu_1} \tag{3}$$

Let T be the total testing time,

Then the probability of r_1 given μ_1 is given by;

$$P(r_1/\mu_1) = \frac{e^{-\mu_1 T}(\mu_1 T)^{r_1}}{r_1!}\ ,\ r_1 = 0, 1, 2, \dots \tag{4}$$

And the probability of r_2 given μ_2 is given by

$$P(r_2/\mu_2) = \frac{e^{-\mu_2 T}(\mu_2 T)^{r_2}}{r_2!}\ ,\ r_2 = 0, 1, 2, \dots \tag{5}$$

The prior distribution of μ_1 is assumed to be $G(\beta_1, \theta_1)$ with p.d.f

$$g_1(\mu_1) = \frac{\theta_1{}^{\beta_1} e^{-\mu_1\theta_1} \mu_1^{\beta_1-1}}{\Gamma(\beta_1)} \tag{6}$$

The prior distribution of μ_2 is assumed to be $G(\beta_2, \theta_2)$ with p.d.f

$$g_2(\mu_2) = \frac{\theta_2{}^{\beta_2} e^{-\mu_2\theta_2} \mu_2^{\beta_2-1}}{\Gamma(\beta_2)} \tag{7}$$

Let the number of failures and repairs recorded in $(0, T)$ be r_1 and r_2 respectively.

Let $U_1 = T + \theta_1$, $U_2 = T + \theta_2$, $a_1 = r_1 + \beta_1$, $a_2 = r_2 + \beta_2$

The posterior distribution of μ_1 given r_1 is

$$\pi_1(\mu_1/r_1) = \frac{P(r_1/\mu_1)g_1(\mu_1)}{\int_0^\infty P(r_1/\mu_1)g_1(\mu_1)d\mu_1} = \frac{(U_1)^{a_1}\mu_1{}^{a_1+1}e^{-\mu_1(U_1)}}{\Gamma(a_1)} \; , \; \mu_1,\, U_1,\, a_1 > 0 \tag{8}$$

which is a gamma distribution $G(a_1, U_1)$.

The posterior distribution of μ_2 given r_2 is

$$\pi_2(\mu_2/r_2) = \frac{(U_2)^{a_2}\mu_1{}^{a_2+1}e^{-\mu_2(U_2)}}{\Gamma(a_2)} \; , \; \mu_2,\, U_2,\, a_2 > 0 \tag{9}$$

which is a gamma distribution $G(a_2, U_2)$.

Since μ_1 and μ_2 are independent variables the posterior distributions of μ_1 given r_1 and μ_2 given r_2 follow gamma distribution, the posterior distribution of A_c given r_1 and r_2 is found to be a beta distribution with parameters a_1 and a_2.

$$f(A_c/r_1, r_2) = \frac{A_c^{a_2-1}(1-A_c)^{a_1-1}}{B(a_2, a_1)} \; , \; 0 < A_c < 1,\, a_2,\, a_1 > 0 \tag{10}$$

The system reliability of L(cons/k-n:F) and C(cons/k-n:F) are presented in [1]. We obtained the following availability functions by combining these reliability functions and the result derived by Griffith and Govindarajulu [29].

The availability function of L(cons/k-n:F) system is given by

$$A_s^L = \sum_{l=0}^{N1}(-1)^l\, C_{N3}^l A_c^l [1 - A_c]^{N4} - \sum_{l=0}^{N1}(-1)^l\, C_{N5}^l A_c^l [1 - A_c]^{N6} \tag{11}$$

The availability function of C(cons/k-n:F) system is given by

$$A_s^C = \sum_{l=0}^{N1}(-1)^l\, C_{N3}^l A_c^l [1 - A_c]^{N4} - \sum_{l=0}^{N2}(-1)^{l+1}\, C_{N7}^l A_c^{l+1} [1 - A_c]^{N6} - [1 - A_c]^n$$

$$N1 = \left\lfloor \frac{n}{k+1} \right\rfloor, N2 = \left\lfloor \frac{n}{k+1} - 1 \right\rfloor, \quad N3 = n - lk, \quad N4 = kl, \quad N5 = n - lk - k,$$

$$N6 = kl + k, N7 = n - lk - k - 1 \tag{12}$$

3. BAYESIAN POINT ESTIMATION

The B.P.E of A_s^L under a SELF is obtained as

$$A_s^{L*} = E[A_s^L/r_1 , r_2] = \int_0^1 A_s^L\, f(A_c/r_1, r_2) dA_c \tag{13}$$

$$A_s^{L*} = \sum_{l=0}^{N1}(-1)^l\, C_{N3}^l \frac{B(a_2+l\, , a_1+N4)}{B(a_2, a_1)} - \sum_{l=0}^{N1}(-1)^l\, C_{N5}^l \frac{B(a_2+l\, , a_1+N6)}{B(a_2, a_1)} \tag{14}$$

The B.P.E of A_s^C under a SELF is obtained as

$$A_s^{C*} = E[A_s^C / r_1, r_2] = \int_0^1 A_s^C\, f(A_c / r_1, r_2) dA_c \tag{15}$$

$$A_s^{C*} = \sum_{l=0}^{N1} (-1)^l\, C_{N3}^l \frac{B(a_2+l, a_1+N4)}{B(a_2,a_1)} - \sum_{l=0}^{N1} (-1)^l\, C_{N7}^l \frac{B(a_2+l+1, a_1+N6)}{B(a_2,a_1)} - \frac{B(a_2, a_1+n)}{B(a_2,a_1)} \tag{16}$$

3.1. Particular cases

Case 1: For series system, when $k = 1$, (14) and (16) are deduced to A_{ss}^*

$$A_{ss}^* = \frac{B(a_2+n, a_1)}{B(a_2,a_1)} \tag{17}$$

Case 2: For parallel system, when $k = n$, (14) and (16) are deduced to A_{sp}^*

$$A_{sp}^* = 1 - \frac{B(a_2, a_1+n)}{B(a_2,a_1)} \tag{18}$$

3.2. Bayesian confidence interval(c_1, c_2)

The interval (c_1, c_2) is said to be a $(1-\alpha)100\%$ confidence interval for A_c if

$$\int_{c_1}^{c_2} f(A_c / r_1, r_2)\, dA_c = 1 - \alpha \tag{19}$$

An equal tail $(1-\alpha)100\%$confidence interval (c_1, c_2) is given by

$$\int_0^{c_1} f(A_c / r_1, r_2)\, dA_c = \frac{\alpha}{2} = \int_{c_2}^1 f(A_c / r_1, r_2)\, dA_c \tag{20}$$

$$\int_0^{c_1} \frac{A_c^{a_2-1}(1-A_c)^{a_1-1}}{B(a_2,a_1)}\, dA_c = \frac{\alpha}{2} = \int_{c_2}^1 \frac{A_c^{a_2-1}(1-A_c)^{a_1-1}}{B(a_2,a_1)}\, dA_c$$
(21)

For a known value of α, the above equation can be used to analyze the interval of availability. The values of c_1 and c_2 in the above equation can be obtained for pre-assigned β_1, β_2, r_1, r_2

4. NUMERICAL RESULTS AND DISCUSSION

B.P.E of steady-state availability for L(cons/k-n:F) and C(cons/k-n:F) system using SELF is obtained in (14) and (16). Furthermore the (14) ad ((16) are analyzed by keeping some of the parameters constant and varying others. Table 1 reveals that the B.P.E of steady-state availability decreases uniformly with an increase in r_1, the number of failures recorded. It shows that there is a 26% increase in A_s^{C*} when compared to A_s^{L*}. It is clearly shown in the Figure 1. It is observed from Table 2, that the B.P.E of steady-state availability increases uniformly with an increase in r_2, the number of repairs It is noticed that the maximum steady state availability is obtained for C(cons/k-n:F) system. From Figure 2, it is observed that C(cons/k-n:F) structure is superior to L(cons/k-n:F) structure by a 24% increase.

The B.P.E of A_{ss} and A_{sp} arededuced in (17) and (18). Using matlab the values of A_{ss}^* and A_{sp}^* are calculated and are tabulated in the Table 3. From (21), 95% Bayesian confidence limits for varying $r_1$is tabulated in Table 4 and for varying $r_2$is given in Table 5. Table 4 reveals that the Bayesian limits for the availability of the system decreases as the number of failures increases. Table 5 reveals that the Bayesian limits for the availability of the system increases as the number of repairs increases.

Table 1. Bayesian estimate of availability for variation in r_1. For $n = 6;\ k = 2;\ \beta_1 = 2;\ \beta_2 = 2;\ r_2 = 2$

r_1	A_s^{L*}	A_s^{C*}	Increase in steady-state availability
1	0.4675	0.6840	0.2165
2	0.3621	0.6177	0.2556
3	0.2844	0.5664	0.2820
4	0.2266	0.5259	0.2993
		Average = 26%	

Table 2. Bayesian estimate of availability for variation in r_2. For $n = 6; k = 2;\ \beta_1 = 2;\ \beta_2 = 2;\ r_1 = 2$

r_2	A_s^{L*}	A_s^{C*}	Increase in steady-state availability
1	0.2727	0.5579	0.2852
2	0.3621	0.6177	0.2556
3	0.4398	0.6690	0.2292
4	0.5063	0.7105	0.2042
			Average = 24%

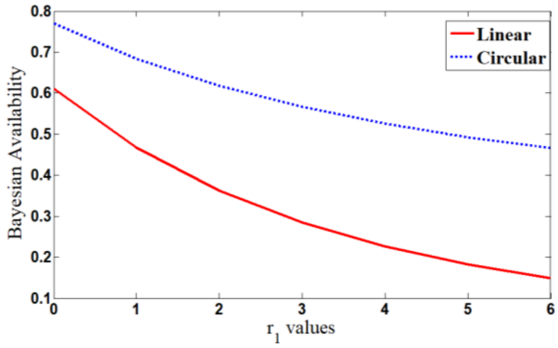

Figure 1. Linear Vs Circular for various values of r_1, when $n = 6;\ k = 2;\ \beta_1 = 2;\ \beta_2 = 2;\ r_2 = 2$

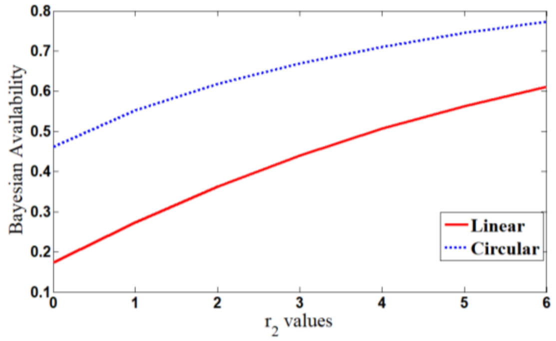

Figure 2. Linear Vs Circular for various values of r_2, when $n = 6;\ k = 2;\ \beta_1 = 2;\ \beta_2 = 2;\ r_1 = 2$

Table 3. Bayesian estimate of A_{ss} and A_{sp} For $n = 6;\ k = 2;\ \ \beta_1 = 2;\ \beta_2 = 2$

	For $r_2 = 2$			For $r_1 = 2$	
r_1	A_{ss}^*	A_{sp}^*	r_2	A_{ss}^*	A_{sp}^*
1	0.0909	0.9697	1	0.0303	0.9091
2	0.0490	0.9510	2	0.0490	0.9510
3	0.0280	0.9301	3	0.0699	0.9720
4	0.0168	0.9077	4	0.0923	0.9832

Table 4. 95% Bayesian confidence interval for different values of r_1
For $n = 6;\ k = 2;\ \ \beta_1 = 2;\ \ \beta_2 = 2;\ \ \alpha = 0.05;\ r_2 = 2$

r_1	Lower limit c_1	Upper limit c_2
1	0.2227	0.7031
2	0.1840	0.6212
3	0.1570	0.5555
4	0.1369	0.5020

Table 5. 95% Bayesian confidence interval for different values of r_2
For $n = 6;\ \ k = 2;\ \ \beta_1 = 2;\ \ \beta_2 = 2;\ \ \alpha = 0.05;\ \ r_1 = 2$

r_2	Lower limit c_1	Upper limit c_2
1	0.2969	0.5532
2	0.3788	0.6212
3	0.4445	0.6710
4	0.4980	0.7091

5. CONCLUSION

In this paper, Bayesian method of estimating steady state availability is described for the proposed system. A particular case with $n = 6$ and $k = 2$ is analyzed numerically. The effect of the number of failures and the number of repairs on the Bayesian estimate of steady-state availability is discussed. The 95% confidence interval for posterior distribution of cons/k-n:F system is tabulated.

The main goal of system maintenance is to improve the availability of the system by maintaining or repairing the equipment in its operating mode. The numerical results indicate that as the number of failures increases, the system's availability decreases and the system's availability increases when number of repairs is increased. In particular A_s^{L*} and A_s^{C*} are independent of time T. Thus, it is concluded that the Bayesian analysis of steady-state availability is not affected as the interval $(0, T)$ varies.

The Bayesian estimate of a cons/k-n:F system's confidence intervals were calculated. The estimate of the confidence interval is obtained by keeping some of the parameters constant and varying r_1 or r_2. For varying r_1, the posterior availability tends to a minimum as the recorded number of failures increases. Similarly, for varying r_2 values, the Bayesian confidence limits for posterior availability appear to be the maximum as the number of repairs increases.

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