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RELIABILITY AND AVAILABILITY ANALYSIS OF DEPENDENT COMPONENTS SYSTEMS

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Abstract

In this study we will discuss the method of availability and reliability of repairable apparatus with s -dependent failures among components. The foundation of system reliability is the dependability of its parts or components. Additionally dependent on component interaction, or s -dependence, is system reliability. There are s -dependent and s -independent in the system. As a result, numerous researchers have examined the accessibility and reliability of the s -dependencies among components; the failure and repair rates were regarded as constants. When we study time-related system reliability with varying failure and rates of repair, the s -dependencies among components are not considered. However, the system reliability and availability, which involve the s -dependent failures and failures varying with time and repair rates, are best suited for simulating actual systems.

This paper tells us about one type of system that resists environmental shocks and the solutions of system availability and reliability with time-varying failure and repair rates. Solutions for mechanical system availability and reliability are exemplified by a particular type of special vehicle.

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Keywords and Phrases: System reliability, Availability, Failure rates, Repair rates.

1 Introduction

A huge intricate system that makes many different functional subsystems. This subsystem can further be separated into various subsystems, components, or elements. The foundation of system reliability is the dependability of its parts or constituents [22]. Reliability of the system is also based upon interactions among the elements and the s -dependence among components. The widely accepted assumption of s -dependence among components is, to some extent, an approximation on some systems, and certain conditions—such as share-load redundant systems can not be represented with the s -independence assumption among components. Hence, in a system we can therefore conclude that not only can there be s -independent failures among components, but also s -dependent failures among them. As a result, numerous studies have considered the s -dependencies among components in system reliability and availability analysis, but they have also assumed constant failure and repair rates.

However, mechanisms of s -dependence among components are so intricate that it is exceedingly challenging to quantify the degree of this s -dependence without making certain assumptions. Studies on s -dependent failure theories for system safety have proliferated recently and have emerged in a variety of engineering domains, including the nuclear, chemical, and oil industries, as well as the mechanical and rocket launch industries. Research mostly focuses on common-cause failures in redundant systems. Consequently, they developed a technique for studying common-cause failures [6].

In this paper we have made an effort to study the system reliability as well availability with interdependent components where failure and repair rate that varies over time. The system dependability has been explored with fluctuating failure and repair rate have been taken in account rather than considering constant thus making the problem more realistic and practically applied in real world situation.

2 Brief Survey of Literature

Many researchers for examples Sharma *et al.* [17, 2007], Walter *et al.* [23, 2008], and Peyghami *et al.* [14, 2020], knowledge-based approximate reasoning methodologies which are required to analyze the reliability because of presented the growing complexity of technological systems. Zhang and Horigome [26, 2001] have obtained reliability and availability of a system with interdependent components and failure that varies over time and rates of repair. Trivedi [21, 2002] derived availability bounds for systems with limited information about the distributions. Ananda [2, 2003] discussed the long-run availability of a system by assuming lognormal repair times and exponential failure times. For system safety, s -dependent failure models have been investigated by El-Damcese and Temraz [5, 2012], which are extensively developed in a variety of engineering domains, including the nuclear, chemical, and oil industries, as well as the mechanical and rocket-launching industries. Vaurio [22, 1995] created a data bank of common cause failures in addition to developing a strategy for assessing them.

Redundant systems in parallel have been described by Shooman [18, 1968], Lin *et al.* [10, 1993], Huang and Xu [7, 2010], and Yang *et al.* [24, 2024], and analysis for parallel repairable systems with degradation facility was done by El-Damcese and Temraz [5, 2012]. Singh [19, 1980] presented the *MCS* technique for expanding the cut-set approach to systems with s -dependencies. The preventative replacement of the system using s -dependent components had been obtained by Albin and Chao [1, 1992]. Okumoto [12, 1981] studied the accessibility of a 2-component dependent system where a shock-damage process has the potential to cause both components to fail at the same time, that is, Poisson with parameter $\lambda_{1,2}$. Temraz [20, 2018] did an analysis of a system consisting of two dependent components with degradation facility and load sharing. Yin *et al.* [25, 2022] and Lesanovsky [9, 1988] presented the multistate Markov models for systems that have s -dependent units, wherein the framework is a homogenous continuous-time Markov process with discrete states, and investigated the system's transition-rate matrix, which is represented by a modified Kronecker total of its units' transition-rate matrices, and introduced an algorithm that determined the Kronecker algebra-based transition-rate matrix. Dorre [4, 1992] explained a stochastic multiple-state explanation on the s -dependent failures and studied the relationship between variability of objective and uncertainty of subjective and the impact of both characteristics on the created result of s -dependent failures. That shows a cohesive approach has both the state of knowledge correlation technique as a framework for explaining subjective parameter uncertainty and the 'generalized model of the binomial distribution function of real-world variability integrated into a multiple-state stochastic quantitative description of systems. The Clayton's framework for s -dependent elements that make up the system reliability was considered by Lyderson [11, 1992]. The main point, a general representation of system reliability in this model, is explained in accordance with the component reliabilities and the s -dependency parameter. The advantage of a model is that it explains the s -dependency regarding a single parameter and also explains the practical interpretation. For use in this model, estimation of s -dependency works as the key.

Humphreys and Jenkins [8, 1991] developed a technique for dealing with s -dependent failures. The method for s -dependent failure problems in real systems has been discussed by Parkinson [13, 1988] in which the failure and repair rates are assumed constant and which all concern s -dependent failures. There are other studies that handled the system reliability of time-varying failure rates. Atwood [3, 1992] has obtained the parametric estimation of time-dependent failure rates for probabilistic risk assessment, in which failures of components are assumed to follow the Poisson process, and it explains many parametric models for the time-dependent failure rate $\lambda(t)$. A concise review of key methodologies for availability, reliability, and maintainability in industrial systems was done by Saini and Kumar [16, 2025]. Rausand and Hoyland [15, 2004] considered the role of mathematical models, statistical methods, and their applications in the practical analysis of maintenance failure data.

3 The Model

The main contents of this paper are divided into three parts.

- i Description of state for repairable system with s -dependent failures.
- ii One type of special vehicle with such mechanical systems illustrates system reliability and availability solutions.
- iii System reliability and availability solutions involve time-varying failure and repair rates.

Assumptions

- i There are two discrete states of system components: one failed and the other operational

- iii Transition of states occurs instantaneously; the probability of two or more states coming into being state transitions in an interval of time dt is $0(dt)$.
- iii Each component has a failure and repair rate that are functions of time.
- iv There are n components of the system, which has a total of 2^n states.
- v A set with k components failed is one failure state of the system regardless of which one is active or passive in the failure mechanism.

Assumptions (iv) and (v) describe s-dependencies among components and also consider splitting component failures into single failure and joint failure.

Let us consider the s-dependencies among components. There can be an occurrence of $1, 2, \dots, k, \dots, n$ components failing simultaneously. Then the system fails. We put the system into repair after failure. After repair, it is put into work again. As we know, that system is always in the failure or operational state $\{ \text{system state } i = 0, 1, \dots, 2^n - 1. \text{ If } i = 0 \text{ such that it is a working state and } i > 0 : \text{ failure states} \}$. System states are defined as

0: The system has n components, which are all operational; thus, the system is operational.

I: The system is in 1 of the following 4 failure types, according to the amount of sdependence, which are:

- i If one component fails, there are ${}^nC_1 = n$ failure states. Then these failure states are written as: $1, 2, \dots, n$.
- ii Two out of n components fail at the same time; there are a total of nC_2 failure states. These failure states are written as follows: $(n+1), (n+2), \dots, (n+{}^nC_2)$, respectively.
- iii Similarly, k out of n components fail simultaneously; there is a total of nC_k failure states. Then these failure states are arranged in this form: $({}^nC_1 + {}^nC_2 + \dots + {}^nC_{k-1} + 1), ({}^nC_1 + {}^nC_2 + \dots + {}^nC_{k-1} + 2), \dots, ({}^nC_1 + {}^nC_2 + \dots + {}^nC_k)$, respectively, continuing in this manner that $(k-1)$ out of the n components are failed.
- iv If all components have failed, then in this case there is only one failure state, $i = \sum_{i=1}^n C_i = 2^n - 1$.

Then $E = \{0, 1, 2, \dots, 2^n - 1\} = \{WUF\}$. If $X(t) = 0$, the components of the system are in operation state. Where E is the state-space, W is the operation - state set $\{0\}$, F is the failure state set: $\{1, 2, \dots, 2^n - 1\}$ and $X(t)$ is the variate of the system state at t .

If $X(t) = I$, the system is in state i , which means that at least one component has failed and $\{X(t), t \geq 0\}$ is a stochastic process whose state space is E .

When failure and repair rates are constant, then this stochastic process becomes a homogeneous Markov process, and this homogeneous Markov process is used to solve such types of problems.

4 Reliability and Availability of Time-Varying Failure and Repair Rates Systems.

Assumptions

1. There are 4 different components of the system.
2. When 1 component fails, then the system fails. When the system has failed, no other components can fail. The system operates under a random environment.
3. At least 2 components can fail simultaneously due to a cumulative shock - damage process caused by environment with $\lambda_i(t)$.
4. At least 3 components can fail simultaneously due to a cumulative shock - damage process caused by environment with $\lambda_i(t)$.
5. When all components fail simultaneously, they are all replaced by new ones so that there is a state transition from this state to the system operative state with $\mu_r(t)$: the system state transition diagram is given in Fig. 4.1.
6. The system has 4 repair facilities, and they all have the same operational proficiency. The failure and repair rates are the function of time, which is shown in Fig. 4.1.

From Fig. 4.1 the equation is:

$$\begin{aligned}
 P'(t) &= T'_R(t)P(t), \\
 P'(t) &=> (P'_0(t), P'_1(t), \dots, P'_{15}(t))^T, \\
 P(t) &=> (P_0(t), P_1(t), \dots, P_{15}(t))^T, \\
 \lambda &= \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_{1,2} + \lambda_{1,3} + \lambda_{1,4} + \lambda_{2,3} + \lambda_{2,4} + \lambda_{3,4} + \lambda_{1,2,3} + \lambda_{1,2,4} + \lambda_{1,3,4} + \lambda_{2,3,4} + \lambda_{1,2,3,4}, \quad (4.1)
 \end{aligned}$$

where, $(P_0(0), P_1(0), \dots, P_{15}(0)) = (1, 0, \dots, 0)$ is the initial condition of (1) and $T'_R(t)$ is the state-transition rate matrix.

In the same way, the above procedure can be solved easily. For n components and the diagram for n components, like as Fig. 4.1, then

$$P'(t) = T_R(t)XP(t), \quad (4.2)$$

where $T_R(t)$ is the transition rate matrix. The initial condition of (4.2) is

$$\begin{aligned} (P_0(0), P_1(0), \dots, P_{2^n-1}(0)) &= (1, 0, \dots, 0), \\ P'(t) &= (P'_0(t), P'_1(t), \dots, P'_{2^n-1}(t))^\top, \\ P(t) &= (P_0(t), P_1(t), \dots, P_{2^n-1}(t))^\top. \end{aligned}$$

$T_R(t)$ and $T'_R(t)$ have the same characteristic. Therefore, the numerical solution for equation (4.2) is possible. We know that there exists a coupling term in this group, which is related to the state-transition rate matrix of differential equation (4.2), and it contains a time-varying factor.

Let us suppose that the factors of equation (4.2) are constant, then on solving equation (4.2) by Laplace transform, we get

$$P_0^*(s) = \frac{\prod_{i=1}^{2^n-1} (s + \mu_i)}{s.H(s)}, s > 0 \text{ and where, } H(s) = \prod_{i=1}^{2^n-1} (s + \mu_i) + \sum_{i=1}^{2^n-1} \lambda_i \prod_{j \neq i}^{2^n-1} (s + \mu_j). \quad (4.3)$$

$P_0^*(s)$ is Laplace transform of $P_0(t)$, and $s > 0$. $H(s)$ is a polynomial of degree $(2^n - 1)$. It has $-S_j$ real roots for all $j = 1, 2, 3, \dots, (2^n - 1)$, such that $H(-S_j) = 0 \forall j = 1, 2, 3, \dots, (2^n - 1)$.

Now taking inverse Laplace transform of (4.3), we find

$$P_0(t) = A_0 + \sum_{j=1}^{2^n-1} A_j e^{-S_j t}, A_0 = \frac{1}{1 + \sum_{i=1}^{2^n-1} \frac{\lambda_i}{\mu_i}}, A_j = \frac{1}{-S_j} \cdot \left[1 + \sum_{i=1}^{2^n-1} \frac{\lambda_i \mu_i}{(-S_j + \mu_i)^2} \right]^{-1}. \quad (4.4)$$

From (4.4), the system-transitory availability is

$$A(t) = P_0(t), \quad (4.5)$$

where $A(t)$ is the steady-state availability, which shows that,

$$A = \frac{1}{1 + \sum_{j=1}^{2^n-1} \frac{\lambda_j}{\mu_j}}. \quad (4.6)$$

Now from Fig. 4.1 the failure state, which is absorbing state, then,

$$R(t) = \exp \left[- \sum_{i=1}^{2^n-1} \lambda_i \right] t, \quad (4.7)$$

$$R_k(t) = \exp \left[- \sum_{i \in G} \lambda_i \right] t, \quad k = 1, 2, \dots, n; \quad (4.8)$$

$G = \{i \mid \text{all figure states containing component } k\}$. If failure and repair rates are not constant in (4.2), then equation (4.2) is known as linear time-varying homogeneous equations; the solution of (4.2) is

$$X(t) = \Phi(t, t_0) \times X(t_0), t \geq t_0;$$

where $\Phi(t, t_0)$ is a non-singular matrix, and $\Phi(t, t_0)$ is the state-transition matrix of a linear time-varying system that depends only on $T_R(t)$. $X(t)$ is the solution vector of (4.2).

Then,

$$\frac{\partial}{\partial t} \Phi(t, t_0) = T_R(t) \times \Phi(t, t_0), \quad (4.9)$$

with initial condition $\Phi(t, t_0) = I$.

The above equation is known as the unique solution of the matrix differential equation. From (4.9) and its initial condition $\Phi(t, t_0) = I$, the result is

$$\frac{\partial}{\partial t} \Phi(t, t_0) \times \Phi^{-1}(t, t_0) = T_R(t). \quad (4.10)$$

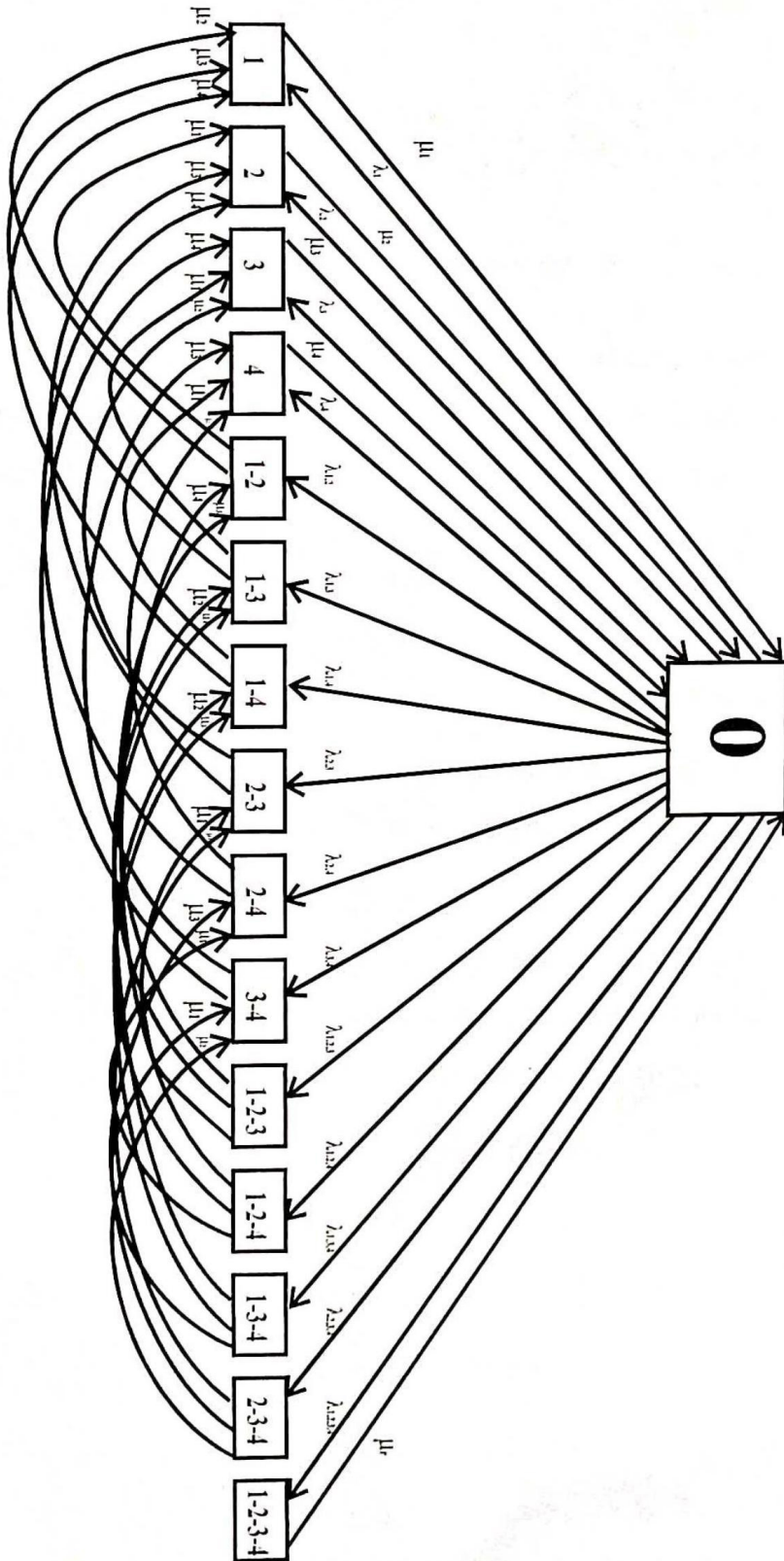


Figure 4.1: System state-transition diagram

Let $\Phi(t, t_0)$ have the simplistic form. Now, integrating equation (4.10) in $[t_0, t]$

$$\begin{aligned}
\int_{t_0}^t \frac{\partial}{\partial t} \Phi(t, t_0) dt &= \int_{t_0}^t T_R(\tau) d\tau, \\
[\log \Phi(t, t_0)]_{t_0}^t &= \int_{t_0}^t T_R(\tau) d\tau, \\
\log \Phi(t, t_0) - \log \Phi(t_0, t_0) &= \int_{t_0}^t T_R(\tau) d\tau, \\
\log \left[\frac{\Phi(t, t_0)}{\Phi(t_0, t_0)} \right] &= \int_{t_0}^t T_R(\tau) d\tau, \\
\frac{\Phi(t, t_0)}{\Phi(t_0, t_0)} &= \exp \int_{t_0}^t T_R(\tau) d\tau, \\
\Phi(t, t_0) &= \Phi(t_0, t_0) \times \exp \int_{t_0}^t T_R(\tau) d\tau.
\end{aligned} \tag{4.11}$$

Function $\Phi(t, t_0)$ and $\Phi(t - t_0)$ are different from each other because $\Phi(t, t_0)$ is a function of t and t_0 and $\Phi(t - t_0)$ is a function of $(t - t_0)$. $\Phi(t - t_0)$ and $\Phi(t - t_0)$ are similar in their characteristic where $\Phi(t - t_0)$ is the state-transition matrix of a linear constant-factor system, and $\Phi(t, t_0)$ is the state-transition matrix of a linear time-varying system. We can write $\Phi(t, t_0)$ in exponential form.

$$\Phi(t - t_0) = \exp \left[\int_{t_0}^t T_R d\tau \right] = \exp [T_R(t - t_0)]. \tag{4.12}$$

$T_R(t)$ is time variant. Therefore $\Phi(t, t_0)$ cannot be found in the form of equation (4.12); if $T_R(t)$ satisfies the condition of result (4.1), then $\Phi(t, t_0)$ can be written as a matrix exponential:

$$\begin{aligned}
\Phi(t, t_0) &= \exp \int_{t_0}^t T_R(\tau) d\tau \\
&= 1 + \int_{t_0}^t T_R(\tau) d\tau + \frac{1}{2!} \left[\int_{t_0}^t T_R(\tau) d\tau \right]^2 + \frac{1}{3!} \left[\int_{t_0}^t T_R(\tau) d\tau \right]^3.
\end{aligned} \tag{4.13}$$

Result 1: $\Phi(t, t_0)$ is the solution of the matrix differential equation of linear time-varying systems from (4.9) with initial condition $\Phi(t_0, t_0) = 1$ that $\Phi(t, t_0) = \exp \left[\int_{t_0}^t T_R(\tau) d\tau \right]$. It will be satisfied when inserting (4.11) into it. Then, the L.H.S. and R.H.S. of (9) are, respectively,

$$\frac{\partial}{\partial t} \Phi(t, t_0) = \exp \left[\int_{t_0}^t T_R(\tau) d\tau \right] \times T_R(t).$$

Therefore, if

$$\exp \left[\int_{t_0}^t T_R(\tau) d\tau \right] \times T_R(t) = T_R(t) \times \exp \left[\int_{t_0}^t T_R(\tau) d\tau \right]. \tag{4.14}$$

If $T_R(t)$ is a matrix with constant elements or a diagonal matrix, then we proved that equation (4.14) is satisfied; otherwise, the solution of $\Phi(t, t_0)$ can be obtained from (4.9), with initial condition $\Phi(t_0, t_0) = I$. That is, when integrating (4.9) in $[t_0, t]$, then

$$\begin{aligned}
\int_{t_0}^t \frac{\partial}{\partial \tau} \Phi(\tau, t_0) d\tau &= \int_{t_0}^t T_R(\tau) \times \Phi(\tau, t_0) d\tau \\
[\Phi(\tau, t_0)]_{t_0}^t &= \int_{t_0}^t T_R(\tau) \times \Phi(\tau, t_0) d\tau.
\end{aligned}$$

Hence,

$$\Phi(t, t_0) = 1 + \int_{t_0}^t T_R(\tau) \times \Phi(\tau, t_0) d\tau. \tag{4.15}$$

Equation (4.15) is extended into a series:

$$\begin{aligned}
\Phi(t, t_0) &= 1 + \int_{t_0}^t T_R(\tau) \times \Phi(\tau, t_0) d\tau \\
&= 1 + \int_{t_0}^t T_R(\tau) \times \left[1 + \int_{t_0}^{\tau} T_R(\tau_1) \times \Phi(\tau_1, t_0) d\tau_1 \right] d\tau \\
&= 1 + \int_{t_0}^t T_R(\tau) d\tau + \int_{t_0}^t T_R(\tau) \times \int_{t_0}^{\tau} T_R(\tau_1) \times \Phi(\tau_1, t_0) d\tau_1 d\tau
\end{aligned}$$

The final solution is:

$$\begin{aligned}
\Phi(t, t_0) &= 1 + \int_{t_0}^t T_R(\tau) d\tau + \int_{t_0}^t T_R(\tau) \times \int_{t_0}^{\tau} T_R(\tau_1) d\tau_1 d\tau \\
&\quad + \int_{t_0}^t T_R(\tau) \times \int_{t_0}^{\tau} T_R(\tau_1) \times \int_{t_0}^{\tau_1} T_R(\tau_2) d\tau_2 d\tau_1 d\tau + \dots
\end{aligned} \tag{4.16}$$

5 Discussion and Conclusion

In this paper we have been discussing the method for analyzing availability and reliability of repairable systems with s -dependent failures among components; failure and repair rates of components are functions of time. Thus, there are many studies where the s -dependencies among components are taken into account in system reliability and availability analysis, but in which failure and repair rates were assumed constant. On the other hand, when we studied system reliability involving time-varying failure and repair rates, in this case the s -dependencies among components were not considered. However, to study system reliability by combining s -dependencies among components and time-varying failure and repair rates is the most appropriate for real systems. But it is very difficult to handle them mathematically; the closed-form solution of system reliability and availability is very difficult to obtain from an analytical solution. Here numerical or simulation methods must be used.

Whereas, with the increase in the number of components in the system, the manipulator time in calculation is enormous, and the calculation requires very large computer memory. The preferable method is used for solving such a problem and simplifying its structure in detail.

This paper analyzes one kind of system that endures environmental shocks and where one or more components can fail simultaneously due to a cumulative shock-damage process. Thus, in all studies concerning s -dependent failures, the failure and repair rates are constant, which becomes unacceptable to knowledgeable practitioners (in recent years) in some situations, especially for mechanical systems.

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