Two-Component Non-Identical Repairable Systems Subjected to Weibull Distribution: Reliability, Availability, and Failure Analysis

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Abstract: ***This study analyzes the reliability and availability of a two-component non-identical repairable system under the Weibull failure distribution with Common Cause Shocks (CCS). Analytical expressions for reliability, MTTF, availability, and failure frequency are derived using a Markov process approach. The results show that the parallel configuration provides higher reliability and availability than the series configuration due to redundancy. Higher Weibull shape parameter (β) and repair rates improve system performance, while common cause failures reduce reliability and availability. The proposed model offers valuable insights for the design, maintenance, and optimization of dependable engineering systems.***

Keywords: Reliability, Availability, Weibull Distribution, Non-identical Components, Common Cause Shocks (CCS), Common Cause Failures (CCF), Repairable Systems, Parallel System Series System, Markov Process, Mean Time to Failure (MTTF), Failure Frequency Function Steady-State Availability, Transient Availability, Stochastic Modelling

1. Introduction

To development and estimation of reliability and availability measures for a two-component non-identical reparable system operating under Weibull failure law in the presence of Common Cause Shocks (CCS). Unlike the identical system analysed in the earlier chapter, the components considered here possess distinct failure characteristics, reflecting real-world engineering systems where heterogeneity between components is common due to design differences, operational stresses, or aging effects.

The main aim of this study is to construct a rigorous framework for quantifying crucial system performance measures—Reliability, Mean Time to Failure (MTTF), Transient State Availability As(t), Steady-State Availability As(∞) and Failure Frequency Function FS(t) — for both series and parallel configurations of the two-component non-identical system. These reliability indices are derived by formulating the underlying probabilistic structure using continuous-time stochastic processes, along with suitable distributional assumptions related to failure and repair behaviours.

A key complexity addressed in this study is the presence of Common Cause Shocks (CCS), which represent shock events that simultaneously induce failure in multiple system components. CCS is a critical reliability issue in safety-critical and high-dependability systems such as power plants, communication networks, medical equipment, industrial process units, and aerospace mechanisms. In such systems, components may not fail independently; instead, they are vulnerable to shared external stresses such as environmental disturbances, vibration bursts, voltage spikes, thermal overload, or operator-induced errors.

Reliability Measures in the Presence of CCS

We study a non-identical two-component system, which is influenced by the intrinsic presence of lethal and non-lethal CCS failures.

The assumptions, Notations and model are as follows

Assumptions

1) The system has two independent components.
2) The system of failures is affected by individual and common cause failures.
3) The components in the system may fail singly at the rate β_I and failure probability is P_1
4) The components fail by common causes at the rate β_c and failure probability is P_2
5) The components are non-identical, and failures follow a Weibull distribution.
6) The individual failures and non-lethal common cause failures occur independently of each other.

Notations

1) β_I = Individual failure rate in a non-identical case
2) β_c = common cause failures rate non-identical case
3) μ = Service rate of individual and non-identical components.
4) R_{NIPS} (t) = Time-dependent Reliability function for a parallel system.
5) R_{NISS} (t) = Time-dependent Reliability function of a series system

2. Mathematical Model

The function allows us to drive and formulate the Availability and Frequency failure function A(t) under the influence of CCFs using a Markovian graph, based on the above assumption. The Markovian graph is given in Figure 4.1. The quantities β_0 , β_1, β_2, μ_0, μ_1, & μ_2 are as follows

$\beta_0 = \left(\frac{1}{\alpha}\right)^{\beta} + \left(\frac{1}{\alpha_c}\right)^{\beta} P_1(1\text{-}P_2)$, $\beta_1 = \left(\frac{1}{\alpha}\right)^{\beta} + \left(\frac{1}{\alpha_c}\right)^{\beta} P_2(1\text{-}P_1)$, $\beta_2 = \left(\frac{1}{\alpha_c}\right)^{\beta} P_1P_2$

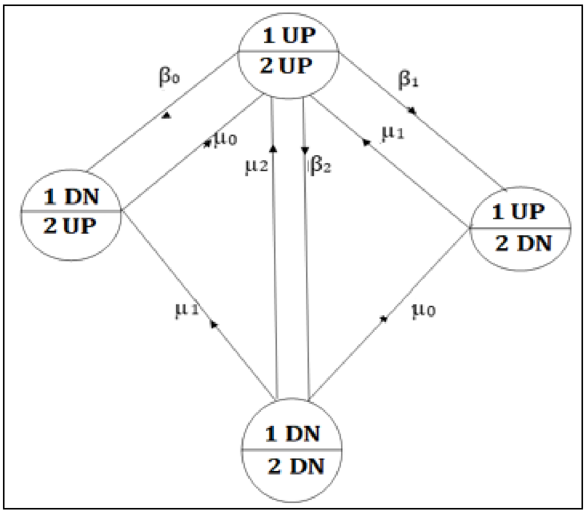

Figure 1: Markovian Graph for Two-Component Non-Identical System in Presence of Intrinsic and CCF

Reliability Function of Non-Identical two Component Non-Repairable Systems

The computed results provide a detailed understanding of how non-identical characteristics and redundancy influence system reliability under different operating conditions.

Table 1: Reliability Function of a Non-Identical Two-Component Parallel System for Different Values of Shape Parameter (β) = 2

S.no	Time(t)	β_0	β_1	β_2	μ_1	μ_2	β	P_1	P_2	$R_{NIPS}(t)$
1	1	0.0007	0.0012	0.0204	0.0100	0.0200	2	0.6000	0.4000	0.9976
2	2	0.0007	0.0012	0.0204	0.0100	0.0200	2	0.6000	0.4000	0.9906
3	3	0.0007	0.0012	0.0204	0.0100	0.0200	2	0.6000	0.4000	0.9791
4	4	0.0007	0.0012	0.0204	0.0100	0.0200	2	0.6000	0.4000	0.9633
5	5	0.0007	0.0012	0.0204	0.0100	0.0200	2	0.6000	0.4000	0.9436
6	6	0.0007	0.0012	0.0204	0.0100	0.0200	2	0.6000	0.4000	0.9203
7	7	0.0007	0.0012	0.0204	0.0100	0.0200	2	0.6000	0.4000	0.8939
8	8	0.0007	0.0012	0.0204	0.0100	0.0200	2	0.6000	0.4000	0.8649
9	9	0.0007	0.0012	0.0204	0.0100	0.0200	2	0.6000	0.4000	0.8339
10	10	0.0007	0.0012	0.0204	0.0100	0.0200	2	0.6000	0.4000	0.8013

Table 2: Reliability Function of a Non-Identical Two-Component Parallel System for Different Values of Shape Parameter (β) = 10

S.no	Time(t)	β_0	β_1	β_2	μ_1	μ_2	β	P_1	P_2	$R_{NIPS}(t)$
1	1	0.0000	0.0000	0.0200	0.0100	0.0200	10	0.6000	0.4000	1.0000
2	2	0.0000	0.0000	0.0200	0.0100	0.0200	10	0.6000	0.4000	1.0000
3	3	0.0000	0.0000	0.0200	0.0100	0.0200	10	0.6000	0.4000	1.0000
4	4	0.0000	0.0000	0.0200	0.0100	0.0200	10	0.6000	0.4000	1.0000
5	5	0.0000	0.0000	0.0200	0.0100	0.0200	10	0.6000	0.4000	1.0000
6	6	0.0000	0.0000	0.0200	0.0100	0.0200	10	0.6000	0.4000	1.0000
7	7	0.0000	0.0000	0.0200	0.0100	0.0200	10	0.6000	0.4000	0.9999
8	8	0.0000	0.0000	0.0200	0.0100	0.0200	10	0.6000	0.4000	0.9998
9	9	0.0000	0.0000	0.0200	0.0100	0.0200	10	0.6000	0.4000	0.9992
10	10	0.0000	0.0000	0.0200	0.0100	0.0200	10	0.6000	0.4000	0.9978

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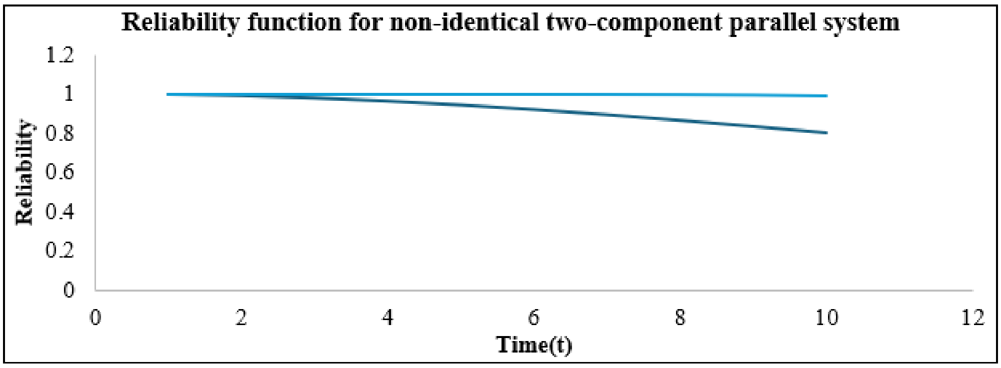


Thus, the expression of the transient state Reliability function for series non-identical components of a series system

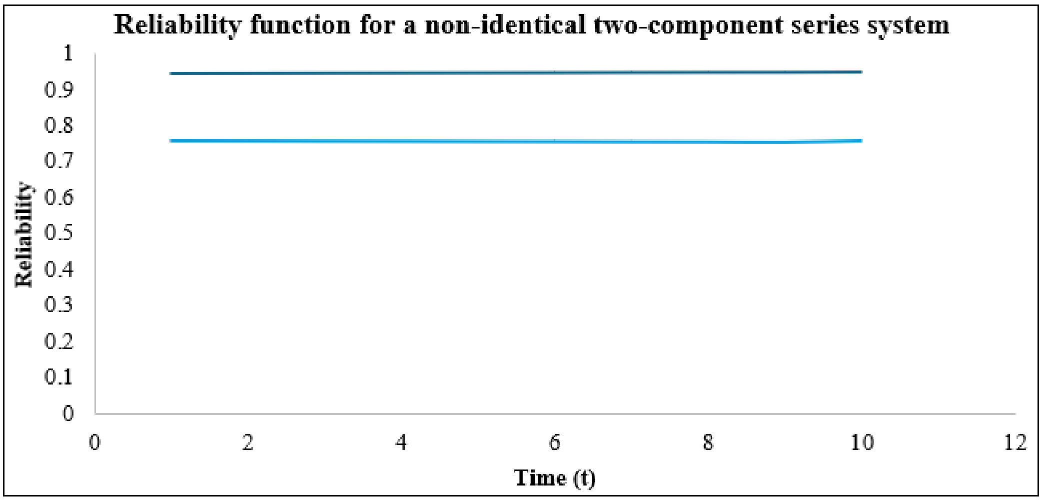
This evaluation helps in understanding how system reliability behaves under stricter structural conditions (series configuration) and how variations in the Weibull shape parameter influence system performance over time.

Table 3: Reliability Function of a Non-Identical Two-Component Series System for Different Values of Shape Parameter (β) = 7

S. No	Time (t)	β_0	β_1	β_2	μ_0	μ_1	μ_2	β	P_1	P_2	$R_{SNS}(t)$
1	1	0.00001	0.00022	0.00000	0.1	0.2	0.3	7	0.3	0.7	0.948017
2	2	0.00001	0.00022	0.00000	0.1	0.2	0.3	7	0.3	0.7	0.948018
3	3	0.00001	0.00022	0.00000	0.1	0.2	0.3	7	0.3	0.7	0.948020
4	4	0.00001	0.00022	0.00000	0.1	0.2	0.3	7	0.3	0.7	0.948021
5	5	0.00001	0.00022	0.00000	0.1	0.2	0.3	7	0.3	0.7	0.948022
6	6	0.00001	0.00022	0.00000	0.1	0.2	0.3	7	0.3	0.7	0.948023
7	7	0.00001	0.00022	0.00000	0.1	0.2	0.3	7	0.3	0.7	0.948025
8	8	0.00001	0.00022	0.00000	0.1	0.2	0.3	7	0.3	0.7	0.948026
9	9	0.00001	0.00022	0.00000	0.1	0.2	0.3	7	0.3	0.7	0.948027
10	10	0.00001	0.00022	0.00000	0.1	0.2	0.3	7	0.3	0.7	0.948029

Table 4: Reliability Function of a Non-Identical Two-Component Series System for Different Values of Shape Parameter (β) = 10

S.NO	Time (t)	β_0	β_1	β_2	μ_0	μ_1	μ_2	β	P_1	P_2	$R_{SNS}(t)$
1.	1	0	0.00001	0	0.1	0.2	0.3	10	0.3	0.7	0.7587
2.	2	0	0.00001	0	0.1	0.2	0.3	10	0.3	0.7	0.7587
3.	3	0	0.00001	0	0.1	0.2	0.3	10	0.3	0.7	0.7587
4.	4	0	0.00001	0	0.1	0.2	0.3	10	0.3	0.7	0.7587
5.	5	0	0.00001	0	0.1	0.2	0.3	10	0.3	0.7	0.7587
6.	6	0	0.00001	0	0.1	0.2	0.3	10	0.3	0.7	0.7587
7.	7	0	0.00001	0	0.1	0.2	0.3	10	0.3	0.7	0.7587
8.	8	0	0.00001	0	0.1	0.2	0.3	10	0.3	0.7	0.7587
9.	9	0	0.00001	0	0.1	0.2	0.3	10	0.3	0.7	0.7587
10.	10	0	0.00001	0	0.1	0.2	0.3	10	0.3	0.7	0.7587



The Availability Function for a Two-Component Non-Identical System

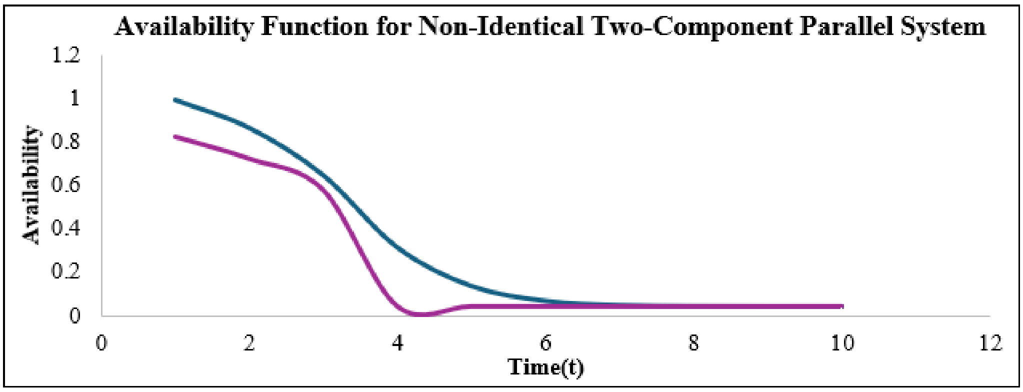
The availability function of a non-identical two-component parallel system is studied considering the effects of individual failures, common cause failures, and repair mechanisms. In a parallel configuration, the system remains operational as long as at least one component is functioning, thereby providing redundancy and improving system availability. The analysis is carried out by varying the time (t) and shape parameter (β), while keeping the service (repair) rates constant at 0.1, 0.2, and 0.3, and repair probabilities at 0.4 and 0.6.

Table 4.10: Availability Function of a Non-Identical Two-Component Parallel System for Shape Parameter (β) = 2

Time	β_0	β_1	β_2	μ_0	μ_1	μ_2	β	P_1	P_2	$A_{NPS}(t)$
1.	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.9957
2.	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.8664
3.	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.6481
4.	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.3152
5.	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.137
6.	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.0684
7.	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.0482
8.	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.0436
9.	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.0428
10.	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.0427

Table 4.14: Availability Function of a Non-Identical Two-Component Parallel System for Shape Parameter (β) = 10

Time	β_0	β_1	β_2	μ_0	μ_1	μ_2	β	P_1	P_2	$A_{NPS}(t)$
1.	0	0	0	0.1	0.2	0.3	10	0.4	0.6	0.8218
2.	0	0	0	0.1	0.2	0.3	10	0.4	0.6	0.7207
3.	0	0	0	0.1	0.2	0.3	10	0.4	0.6	0.5765
4.	0	0	0	0.1	0.2	0.3	10	0.4	0.6	0.0425
5.	0	0	0	0.1	0.2	0.3	10	0.4	0.6	0.0425
6.	0	0	0	0.1	0.2	0.3	10	0.4	0.6	0.0425
7.	0	0	0	0.1	0.2	0.3	10	0.4	0.6	0.0425
8.	0	0	0	0.1	0.2	0.3	10	0.4	0.6	0.0425
9.	0	0	0	0.1	0.2	0.3	10	0.4	0.6	0.0425
10.	0	0	0	0.1	0.2	0.3	10	0.4	0.6	0.0425



Series System

In a series configuration, the system operates only when both components are functioning simultaneously. Therefore, the system is highly sensitive to failures, as the failure of any one component leads to complete system failure. The analysis is carried out by varying time (t) and shape parameter (β), while maintaining constant service (repair) rates of 0.1, 0.2, and 0.3, and repair probabilities of 0.4 and 0.6.

Table 4.15: Availability Function of a Non-Identical Two-Component Series System for Shape Parameter (β) = 2

S.no	Time	β_0	β_1	β_2	μ_0	μ_1	μ_2	β	P_1	P_2	$A_{NSS}(t)$
1.	1	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.4133
2.	2	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.4100
3.	3	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.2018
4.	4	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.1398
5.	5	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.0890
6.	6	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.0630
7.	7	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.0523
8.	8	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.0488
9.	9	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.0478
10.	10	0.0092	0.0091	0.0014	0.1000	0.2000	0.3000	2	0.4000	0.6000	0.0476

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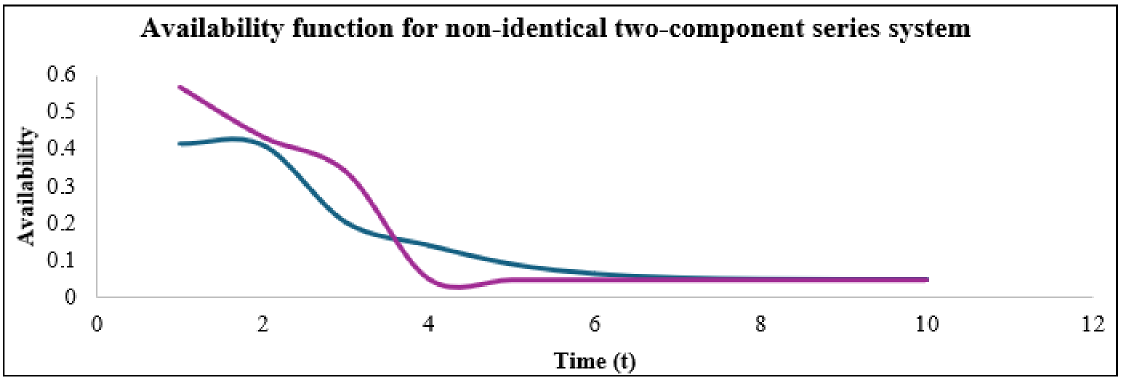
Table 4.19: Availability Function of a Non-Identical Two-Component Series System for Shape Parameter (β) = 10

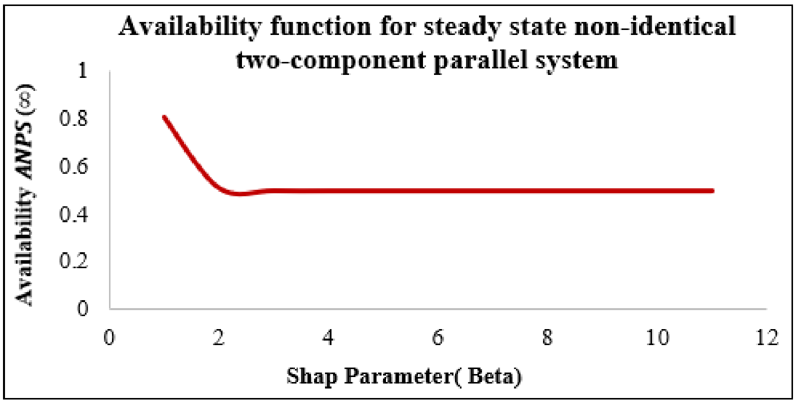
S.no	Time	β_0	β_1	β_2	μ_0	μ_1	μ_2	β	P_1	P_2	$A_{NSS}(t)$
1	1	0.0000	0.0000	0.0000	0.1000	0.2000	0.3000	10	0.4000	0.6000	0.5691
2	2	0.0000	0.0000	0.0000	0.1000	0.2000	0.3000	10	0.4000	0.6000	0.4344
3	3	0.0000	0.0000	0.0000	0.1000	0.2000	0.3000	10	0.4000	0.6000	0.3408
4	4	0.0000	0.0000	0.0000	0.1000	0.2000	0.3000	10	0.4000	0.6000	0.0503
5	5	0.0000	0.0000	0.0000	0.1000	0.2000	0.3000	10	0.4000	0.6000	0.0477
6	6	0.0000	0.0000	0.0000	0.1000	0.2000	0.3000	10	0.4000	0.6000	0.0477
7	7	0.0000	0.0000	0.0000	0.1000	0.2000	0.3000	10	0.4000	0.6000	0.0477
8	8	0.0000	0.0000	0.0000	0.1000	0.2000	0.3000	10	0.4000	0.6000	0.0477
9	9	0.0000	0.0000	0.0000	0.1000	0.2000	0.3000	10	0.4000	0.6000	0.0477
10	10	0.0000	0.0000	0.0000	0.1000	0.2000	0.3000	10	0.4000	0.6000	0.0477



The graph illustrates the variation of availability with respect to time for different values of the shape parameter (β).

Table 4.20: Steady-State Availability Function for Non-Identical Two-Component Parallel System

S.NO	β_0	β_1	β_2	μ_0	μ_1	μ_2	β	P_1	P_2	$A_{NSPS}(\infty)$
1.	0.1069	0.1210	0.0162	0.1	0.2	0.3	1	0.3	0.7	0.8073
2.	0.0105	0.0098	0.0012	0.1	0.2	0.3	2	0.3	0.7	0.5124
3.	0.0010	0.0008	0.0001	0.1	0.2	0.3	3	0.3	0.7	0.5013
4.	0.0001	0.0001	0.0000	0.1	0.2	0.3	4	0.3	0.7	0.5006
5.	0.0000	0.0000	0.0000	0.1	0.2	0.3	5	0.3	0.7	0.5006
6.	0.0000	0.0000	0.0000	0.1	0.2	0.3	6	0.3	0.7	0.5006
7.	0.0000	0.0000	0.0000	0.1	0.2	0.3	7	0.3	0.7	0.5006
8.	0.0000	0.0000	0.0000	0.1	0.2	0.3	8	0.3	0.7	0.5006
9.	0.0000	0.0000	0.0000	0.1	0.2	0.3	9	0.3	0.7	0.5006
10.	0.0000	0.0000	0.0000	0.1	0.2	0.3	10	0.3	0.7	0.5006

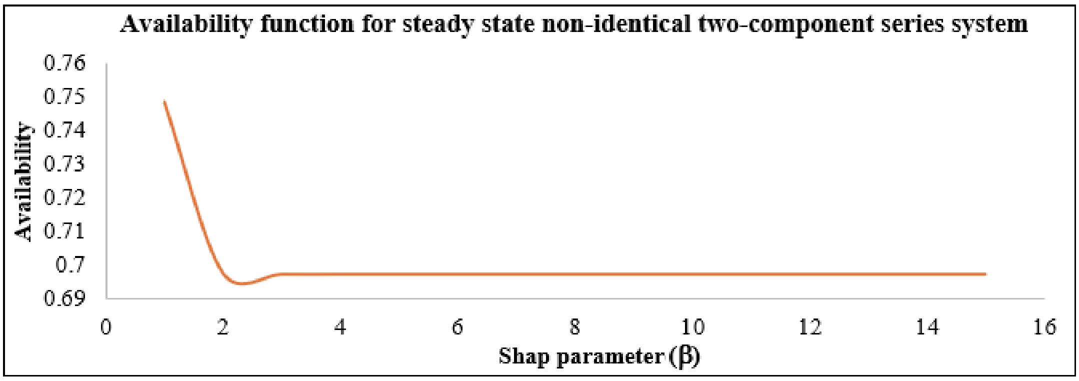


Series System

For a series configuration, system functionality is contingent upon the uninterrupted operation of *all* components.

Table 4.20: Steady-State Availability Function for Non-Identical Two-Component Series System

S.NO	β_0	β_1	β_2	μ_0	μ_1	μ_2	β	P_1	P_2	$A_{NSSS}(\infty)$
1.	0.0135	0.0099	0.0023	0.5	0.8	0.9	1	0.6	0.4	0.7484
2.	0.0001	0.0001	0.0012	0.5	0.8	0.9	2	0.6	0.4	0.6978
3.	0.0000	0.0000	0.0000	0.5	0.8	0.9	3	0.6	0.4	0.6974
4.	0.0000	0.0000	0.0000	0.5	0.8	0.9	4	0.6	0.4	0.6974
5.	0.0000	0.0000	0.0000	0.5	0.8	0.9	5	0.6	0.4	0.6974
6.	0.0000	0.0000	0.0000	0.5	0.8	0.9	6	0.6	0.4	0.6974
7.	0.0000	0.0000	0.0000	0.5	0.8	0.9	7	0.6	0.4	0.6974
8.	0.0000	0.0000	0.0000	0.5	0.8	0.9	8	0.6	0.4	0.6974
9.	0.0000	0.0000	0.0000	0.5	0.8	0.9	9	0.6	0.4	0.6974
10.	0.0000	0.0000	0.0000	0.5	0.8	0.9	10	0.6	0.4	0.6974

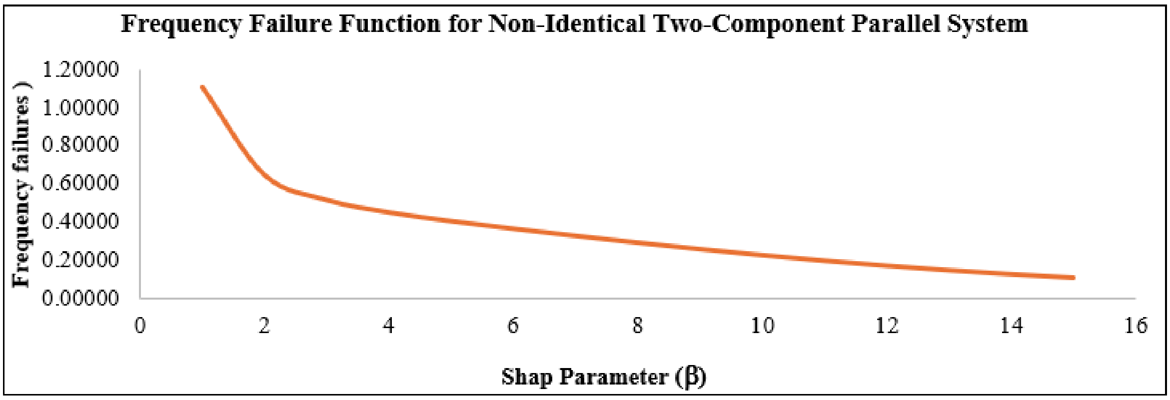


The Function of Frequency Failure Function for Non- Identical Component System

In this section derived and discussed the frequency failure function for series and parallel as follows.

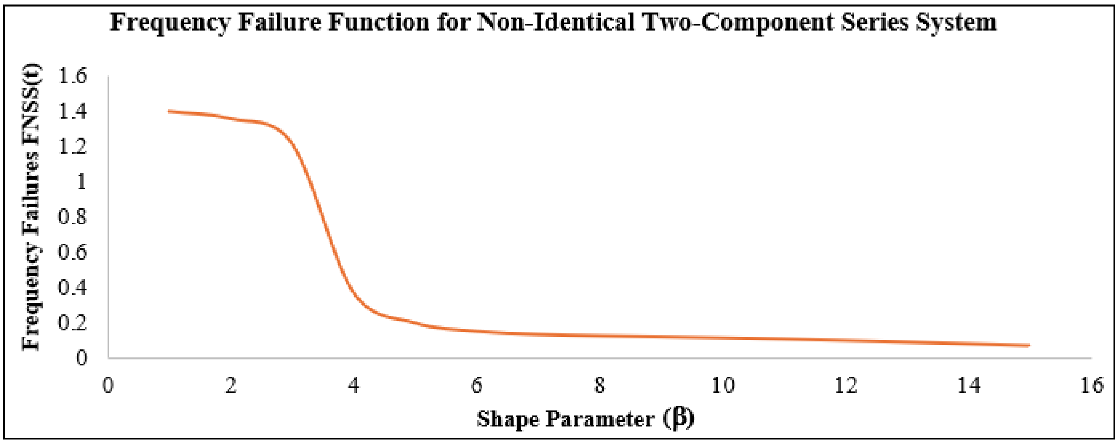
Table 4.21: Frequency of Failures for Non-Identical Two-Component Parallel System

Time	β_0	β_1	β_2	μ_0	μ_1	μ_2	β	P_1	P_2	$F_{NPS}(t)$
1.	1.1067	0.94	0.16	0.0007	0.0008	0.0009	1	0.4	0.6	1.1116
2.	1.0711	0.7656	0.1067	0.0007	0.0008	0.0009	2	0.4	0.6	0.6483
3.	1.0474	0.6261	0.0711	0.0007	0.0008	0.0009	3	0.4	0.6	0.516
4.	1.0316	0.5139	0.0474	0.0007	0.0008	0.0009	4	0.4	0.6	0.4506
5.	1.0211	0.4229	0.0316	0.0007	0.0008	0.0009	5	0.4	0.6	0.4043
6.	1.014	0.3489	0.0211	0.0007	0.0008	0.0009	6	0.4	0.6	0.3644
7.	1.0094	0.2884	0.014	0.0007	0.0008	0.0009	7	0.4	0.6	0.3268
8.	1.0062	0.2388	0.0094	0.0007	0.0008	0.0009	8	0.4	0.6	0.291
9.	1.0042	0.198	0.0062	0.0007	0.0008	0.0009	9	0.4	0.6	0.2569
10.	1.0028	0.1643	0.0042	0.0007	0.0008	0.0009	10	0.4	0.6	0.225
11.	1.0018	0.1364	0.0028	0.0007	0.0008	0.0009	11	0.4	0.6	0.1957
12.	1.0012	0.1134	0.0018	0.0007	0.0008	0.0009	12	0.4	0.6	0.1691
13.	1.0008	0.0943	0.0012	0.0007	0.0008	0.0009	13	0.4	0.6	0.1453
14.	1.0005	0.0784	0.0008	0.0007	0.0008	0.0009	14	0.4	0.6	0.1242
15.	1.0004	0.0653	0.0005	0.0007	0.0008	0.0009	15	0.4	0.6	0.1058



The system is influenced by different failure rates of components along with interaction effects. The variation of failure frequency with respect to the shape parameter β is studied to understand how system failure behavior evolves under increasing failure intensity conditions.

Time	β_0	β_1	β_2	μ_0	μ_1	μ_2	β	P_1	P_2	$F_{NSS}(t)$
1.	1.0119	0.9478	0.1786	1	2	3	1	0.5	0.5	1.4036
2.	0.822	0.7193	0.1276	1	2	3	2	0.5	0.5	1.3629
3.	0.6698	0.5463	0.0911	1	2	3	3	0.5	0.5	1.2225
4.	0.5473	0.4152	0.0651	1	2	3	4	0.5	0.5	0.374
5.	0.4484	0.3158	0.0465	1	2	3	5	0.5	0.5	0.2005
6.	0.3681	0.2404	0.0332	1	2	3	6	0.5	0.5	0.1521
7.	0.3028	0.1831	0.0237	1	2	3	7	0.5	0.5	0.1345
8.	0.2495	0.1395	0.0169	1	2	3	8	0.5	0.5	0.1264
9.	0.2059	0.1064	0.0121	1	2	3	9	0.5	0.5	0.121
10.	0.1701	0.0812	0.0086	1	2	3	10	0.5	0.5	0.1153
11.	0.1408	0.062	0.0062	1	2	3	11	0.5	0.5	0.1083
12.	0.1166	0.0473	0.0044	1	2	3	12	0.5	0.5	0.1001
13.	0.0966	0.0362	0.0031	1	2	3	13	0.5	0.5	0.0909
14.	0.0801	0.0276	0.0022	1	2	3	14	0.5	0.5	0.0811
15.	0.0665	0.0211	0.0016	1	2	3	15	0.5	0.5	0.0714



The frequency of failures for the non-identical two-component series system:

- Decreases monotonically with increasing β,
- Shows a significant drop after β ≥ 4, indicating system stabilization,
- Approaches a low limiting value (~0.0714) for higher β values.

This indicates that although the series system is initially failure-prone, improved conditions (lower effective failure rates) can significantly reduce failure occurrence over time

3. Conclusions

This study developed a reliability model for a two-component non-identical repairable system under the Weibull failure law with Common Cause Shocks (CCS). Using a continuous-time Markov approach, analytical expressions for reliability, availability, MTTF, and failure frequency were derived for both series and parallel configurations. The results show that the parallel system provides superior reliability and availability due to redundancy, while the series system is more sensitive to component and common cause failures. Higher Weibull shape parameter (β) and repair rates improve system performance, whereas common cause failures significantly reduce reliability. The proposed model provides useful guidance for designing and maintaining more reliable engineering systems.

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