Original Research

Performance Assessment of a Serial System with Human Operators Attended by Repair Machines

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Abstract

Repair machines play a critical role in military, communication, industrial, and manufacturing settings. This study investigates the performance of a system that utilizes repair machines with human operators, employing Copula's attributes for estimation. The research focuses on a serial system composed of two subsystems, each consisting of two active components running in parallel. Both subsystems are manned by two human operators and assigned two repair machines for operation and maintenance, where the repair machines are considered failure-prone systems. The system experiences partial and complete malfunction during operation: Partial malfunction lead the system into reduced capacity mode, and a complete malfunction resulting in system failure. The research employs the technique of supplementary variable and transforms of Laplace to establish and solve the governing differential equations corresponding to schematic system's diagram. Performance models for the system such as profit, MTTF, availability, sensitivity of MTTF and reliability are numerically validated and presented through tables and graphs. These findings are highly valuable for evaluating performance, identifying ideal system designs, and developing workable maintenance plans. The research contributes to enhancing system performance, increasing production output, and improving revenue mobilization in various application domains.

Keywords- Reliability; Human operator; Availability; Repair machine; Mean time to failure; Cost function

INTRODUCTION

In the manufacturing and industrial sectors, the use of metrics of reliability like profit, dependability, mean time to failure (MTTF), and availability is currently widespread. With the progress made in the field of technology, the progress of production from industrial and manufacturing settings is linked to the overall development of production output. In order to avoid the risk of their breakdown, the systems must therefore be in good condition. In modern industries, many complex systems rely on a series of sequential operations to achieve their objectives. These serial systems often involve the collaboration of human operators and automated machines to perform specific tasks. The efficiency and reliability of such systems are crucial for maintaining productivity and minimizing downtime. To ensure optimal performance, a comprehensive performance assessment becomes essential. Indeed, the integration of human operators and automated machines in serial systems has become increasingly prevalent in modern industries. These systems offer a combination of human decision-making capabilities and the speed and precision of machines, leading to improved efficiency and productivity. However, this integration also introduces new challenges that must be addressed to maintain a high level of performance.

In industrial and manufacturing settings, human operators play a crucial role in operating and maintaining complex systems and machinery. However, human error is a significant factor that can impact system reliability and performance. Human errors can occur due to various reasons, such as cognitive limitations, fatigue, stress, inadequate training, and environmental factors. By conducting reliability and performance assessments considering human factors, industrial and manufacturing organizations can identify potential vulnerabilities, develop targeted interventions and training programs, and improve the overall safety and efficiency of their systems. Such studies are crucial in high-risk industries to prevent accidents, enhance system reliability, and optimize human-technology interactions.

There is a wealth of literature on the subject of human-robot-repair machine or facilities collaboration aimed at boosting productivity, efficiency, and reducing workplace accidents. Chen and colleagues (2020) have presented one of these approaches that holds promise for enhancing the effectiveness and security of tasks involving human-robot collaboration. Their method enables the detection of human intentions as well as a more precise and trustworthy estimating the stiffness of the human arm. Matheson et al. (2019) emphasize the difficulties and factors to consider when deploying collaborative robotics in manufacturing environments. These include guaranteeing safety, providing proper worker training, and effectively integrating robots into established production processes. Hiatt and co-authors (2017) stressed the value of working together in human-robot cooperation and emphasized the potential difficulties that could arise as a result of individual differences that could obstruct shared comprehension. Goida et al. (2018) introduced an approach to measure the improvements in productivity resulting from the replacement of human labor with industrial robots. In Gao (2021), the availability, dependability and reliability attributes of a fixable resilient equipment that includes warm component standbys and an optional supplementary service are primarily examined.

Wu et al. (2016) examined a k-out-of-n configuration fixable system and incorporated a replaceable equipment. The elements within the system exhibit random distributions for their lifetimes and repair durations, rather than following exponential patterns. When a component experiences a malfunction or failure, it undergoes repair with the help of the service assistant, where itself can malfunction during the service process and subsequently get substituted by a brand new one. Dhillon and Misra (1985) formulated mathematical models to analyze and evaluate the reliability of redundant systems that take into account the presence of critical human errors. Dhillon and Rayapati (1985) delves into Markovian modelling of non-maintained parallel systems to assess the durability, dependability and mean time to failure, considering both hardware malfunction and errors caused by human. Gupta and Sharma (1986) examined the dependability, mean time to failure (MTTF) and reliability of a repairable electronic equipment comprising some units in a redundant attachement, where both units have two operational states, while considering the influence of human errors.. The presence of human failures leads to a complete malfunction of the equipment. Lado and Singh (2019) conducted a study to investigate the resilience of a serial equipment composed of two subsystems, considering the influence of a human operator.

The exemplary synergy of human-machine collaboration is exemplified in Ghasemi and Babaeinesami (2020) research, which centers on optimizing equipment utilization in fire stations and reducing response time to incidents. They achieved this by efficiently managing referral calls to the 125 Sari fire station center, ensuring that calls are directed to the nearby fire station to minimize unanswered calls and eliminate the need for redirection to other stations whenever possible. However, Copula's attributes for estimation, which involves a statistical method for modelling the joint distribution of variables in not capture. Also, the study failed to address the degree and the types of failure involve in the study. Human errors represent a significant contributor to the malfunction of production equipment. Mistakes made by human operators have resulted in interruptions to the process of production, reduced quality, losses in production, diminished income, and increased service expenses. Consequently, to mitigate the risk of system downtime, it is advisable to replace human labor with automated repair machines, especially when addressing partial system failures during maintenance. Repair machines are systems designed for precision and high-speed maintenance of the system. Repair machines may operate in harsh environments or in weather conditions that are not favorable to humans. The systems should be repaired using general repair as a result of achieving maximum efficiency where it is incomplete malfunction, and where it has completed malfunction condition, it should be repaired using copula repair as it predicts better efficiency and improves system durability and dependability compared to general repair.

With the advances made in the technological sector, repair machines have been introduced to cater for the maintenance of certain manufacturing and industrial systems. The implementation of automated repair machinery in maintenance tasks has become imperative in response to the challenges confronted by human repair workers in specific manufacturing and industrial sectors, particularly those with inherent hazards such as nuclear power, highways, power lines, aerospace, and the diagnosis of diseases like COVID-19 and Ebola. In some advanced nations, robots have been integrated into maintenance operations, especially for tasks that involve high risks to human well-being. These repair machines essentially become an integral part of the system, and their deployment aims to enhance system efficiency by handling maintenance tasks that pose potential dangers to human repair personnel.

Literature Review

Many scholars have acknowledged their findings in the field of durability and dependability examination by investigating the behavior of intricate fixable equipment in diverse failure scenarios and repair distribution patterns. For instance, Gulati et al. (2016) studied the dependability assessment of an intricate structure configured in a series configuration while taking into account various failure modes and repair techniques using copula analysis. The dependability and accessibility examination of standby devices that take into account engaged vacations and the subsequent testing of failed components was investigated by Yang et al. in 2019. Abubakar et al. (2019) used a copula semantic approach to evaluate the efficiency of industrial machinery as part of their investigation. Considering cruise qualities, Zhao et al. (2020) carried out an examination of reliability of an aero-engine compressor rotor system. An investigation on the dependability and accessibility assessment of standby systems that take into account engaged vacations and the subsequent testing of failed components was presented by Yang et al. in 2019 meanwhile. The technique to evaluate an industrial mechanism's dependability and economic viability using a cost-free assurance policy has been proposed by Niwas and Garg (2018).

In a different study, Ram et al. (2015) examined how well a 1-out-of-2: G initiative performs when flawless modification is used. By applying the distribution of Gumbel-Hougaard family copula, Lado and Singh (2019) examined the expenditure of serviceable equipment made up of two parts into the organized in a series configuration. In the meantime, Singh et al. (2013) presented an accuracy evaluation of a fuzzy logic-based obstruction optimization method for sensor networks. Berk et al. (2019) presented durability assessment of safety-critical sensor information. The resiliency of non-repairable phased-mission structures with typical bus efficiency sharing was studied by Yu et al. (2018) and presented. Zhang (2019) offered study on a cognitive cloud computing method-based dependability evaluation of computer networks. Considering the impact of weather conditions, Kumar et al. (2020) investigated the dependability evaluation of a backup system that employs a First-Come-First-Served (FCFS) repair policy. The dependability of the assessment of a hierarchical structure that faces differing prior information as well as multilevel data has been dealt with by Yang et al. (2019).

Temraz (2019) developed an approach for evaluating a parallel mechanism's availability and dependability while taking into account insufficient repair and replacement, which involved examination and cost efficiency. The dependability examination of a communication equipment with relay stations was investigated by Yusuf et al. (2020), who took into consideration both limited and total malfunctions. Gahlot et al. (2018) employed copula technique to evaluate the efficacy of a fixable mechanism set up in a series setup while taking into account multiple failure types and repair strategies. The dependability evaluation of a fixable network system made up of three computer labs linked to a server using a 2-out-of-3: G setup was examined in detail by Singh et al. (2020). The cost and effectiveness evaluation of a complicated fixable system with two parts linked in a series was the focus of a study carried out by Lado et al. (2018). Research on dependability metrics for a structure made up of two parts in a series configuration using copula methodology was presented by Singh and Ayagi (2017). For a three-unit gas turbine power plant, Rajesh et al. (2018) investigated the study of accessibility and reliability examination. A linear sequential 2-out-of-4 structure linked to a 2-out-of-4 assisting device for execution was described for specific reliability attributes by Yusuf et al. (2018). A serial system with a single human operator was the subject of Lado and Singh's (2019) cost assessment study. Ismail et al. (2021) investigated a two-subsystem series-parallel system with two human operators monitoring each subsystem.

The body of literature mentioned above has laid out its findings on performance and reliability examination of a few serial systems and declared an improvement in the efficiency of the system. However, a notable gap in copula-based studies exists, specifically in the realm of comprehensive reliability, durability, performance and dependability examination for serial systems attended by two human operators in which the partial malfunction is corrected by fixable machines. These systems are characterized by the presence of human operators and comprise diverse subsystems with maintenance operations overseen by repair machines. To address this research gap, this paper investigates a serial system comprising two interconnected subsystems, each attended by a human operator and a repair machine. The repair machines are themselves susceptible to failure and are responsible for restoring partially failed units within their respective subsystems.

The majority of reliability and performance analysis concerning complex systems tend to concentrate on performance enhancement of the systems under various types of failure and distribution of repairs. These often come with high handling costs and the failures can severely impact the production process. The copula-based strategy for dependability and system efficiency analysis, that allows the modeling of connections among various system components, has not been sufficiently covered in prior literature. With this method, it is acknowledged that the efficiency of a system is frequently influenced by interactions between all of its parts rather than just by the individual performances of each component. Considering the interrelationships between the system's components, the use of copulas makes it possible to represent the system's overall probability distribution. This method enables a more accurate assessment of the system's overall performance and dependability, an important factor in sectors where system failure or downtime can result in significant financial losses and reputational damage.

The copula approach offers a valuable tool for analyzing the performance of manufacturing systems, taking into account the complex interactions between their components. The primary goal of the paper is to obtain essential reliability metrics, including reliability, availability, mean time to failure (MTTF), sensitivity analysis, and the profit function. The study's overarching objective is to develop reliable models that enable a comprehensive analysis of the system's strength. By providing a deeper understanding of system reliability and performance, this paper can inform decision-making and support better planning and utilization of repair machines in diverse operational contexts. The current research is significant in advancing the understanding of repair machines and human operator interactions in critical systems. It contributes to the development of optimal system designs and maintenance strategies, which can have far-reaching implications for various industries, leading to increased efficiency and productivity. The system considered in the study involves failure-prone repair machines, which can be seen as a critical aspect of the research. By studying failure patterns and analysing the two types of failures (Type I and Type II), the research may offer valuable insights into system reliability and availability. By using this approach, industries can make more informed decisions about the design, maintenance, and operation of their manufacturing systems, ultimately leading to more dependable and reliable operations. The contribution of the study can be summarized as follows:

1. The study focuses on the performance evaluation of a system that utilizes a repair machines scheme employing human operators. The research emphasizes the significance of this evaluation in various settings such as military, communication, industrial, and manufacturing sectors.
2. The study delves into reliability measures considered in determine the reliability, performance, and strength of a serial system composed of two subsystems. Each subsystem consists of two active components running in parallel, with two human operators and two repair machines assigned to each for operation and repair.

3. The research considers complete and partial malfunction in the system operation. Partial malfunction is a failure leading to reduced system capacity, while complete malfunction results in complete system failure. The repair machines are responsible for fixing the incomplete failures.
4. The research utilizes mathematical methods including Copula attributes, technique od supplementary variable, and transformation of Laplace. These methodologies are employed to formulate and address the governing differential equations linked to the system schematic diagram, which are crucial for the study.
5. The research provides numerical validation of explicit expressions for MTTF sensitivity, availability, Mean Time To Failure (MTTF), profit function and reliability. The results are illustrated in graphical and tabular scheme.
6. The study's findings should offer useful information for assessing efficiency, choosing the best equipment design, and choosing realistic service strategies. These findings can be used in a variety of industrial and manufacturing contexts to improve system performance, boost production output, and increase the generation of revenue.

The study is structured into several sections. Section 2 delves into the pertinent literature relevant to the proposed model. Section 3 encompasses the state description and the notation employed for analyzing the proposed model. Section 4 is dedicated to presenting reliability models of the system, with specific cases discussed. Finally, the study concludes with the results illustrated in Section 5.

NOTATIONS AND STATE DESCRIPTION

- *NOTATIONS*

q : representing time variable.

s: representing variable of transformation of Laplace

δ_1 : rate of failure representation

δ_2 : B1 and B2 rate of failure representation

δ_3 : rate of failure representation of machine 1

δ_4 : rate of failure representation of machine 2

δ_{H1} : A1 and A2 rate of failure representation due to human mistake 1

δ_{H2} : B1 and B2 rate of failure representation due to human mistake 2

$v_1(r_1)$: A1 and A2 rate of repair representation

$v_2(r_1)$: B1 and B2 rate of repair representation

$v_0(r_1)$: rate of repair representation for complete failed states in subsystem 1 and 2

$v_0(r_2)$: rate of repair representation for complete malfunction state of subsystem 1 due to human mistake 1

$v_0(r_5)$: rate of repair representation for complete malfunction state of subsystem 1 due to human mistake 2

$v_0(r_3)$: rate of repair representation for complete malfunction state of Repair machine 1

$v_0(r_4)$: rate of repair representation for complete malfunction state of Repair machine 2

$T_i(q)$: stand for chance of the equipment staying in any state at instants for i =0 to 10

$\bar{T}_0(s)$: representation for transformation of Laplace with probability $T(q)$

$T_k(r_1,q)$: representation for chance of the system staying in any state with service duration is (r1, q) with service variable r1 and time q

$T_k(r_2,q)$: representation for chance of the equipment sojourning in any state for i=1…….8, the with service duration is (r2, q) with service r2 and time q

$E_p(q)$: profit anticipation profit in $[0,q)$

G_1, G_2 : income and cost of service cost per unit time, respectively.

$v_0(r)$: representation of joint probability according to Gumbel-Hougaard family Copula definition is given as (failed state Si to good state S0)

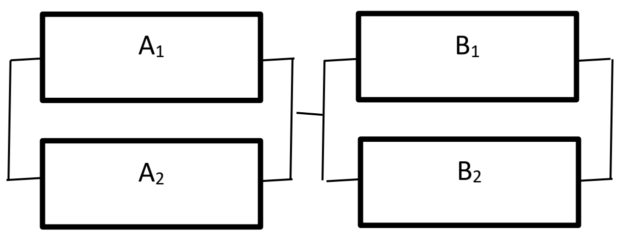


FIGURE 1
EQUIPMENT BLOCK DIAGRAM

S0: Represent initial state, which is free from any failures.

S1: In subsystem 1, represent the initial malfunction of the unit, with the repair being carried out by repair machine 1.

S2: In subsystem 2, depict the initial malfunction of the unit, with the repair being conducted by repair machine 2.

S3: Illustrate in subsystem 1 the occurrence of the second unit malfunction.

S4: Represent the state where subsystem 2 experiences complete malfunction because of the second unit failing, following the previous malfunction of the first unit.

S5: Indicate the state where subsystem 1 initially experiences a partial malfunction, followed by malfunction of a unit in subsystem 2, while repair machines 1 and 2 are engaged in repairing the faulty units

S6: Specify the state where an incomplete failure occurs in subsystem 2 initially, followed by malfunction of a unit in subsystem 1, while repair machine 2 and 1 are engaged in repairing the faulty units.

S7: Indicate complete malfunction state of the system caused by the failure of subsystem 1 due to the actions of human operator 1.

S8: Specify the complete malfunction state of the system resulting from the failure of subsystem 2, which was caused by human operator 2.

S9: Specify the complete state of repair for machine 1 resulting from the repair of a failed unit in subsystem 1.

S10: Indicate the full state of repair for machine 2 as a result of fixing a failed unit in subsystem 2.

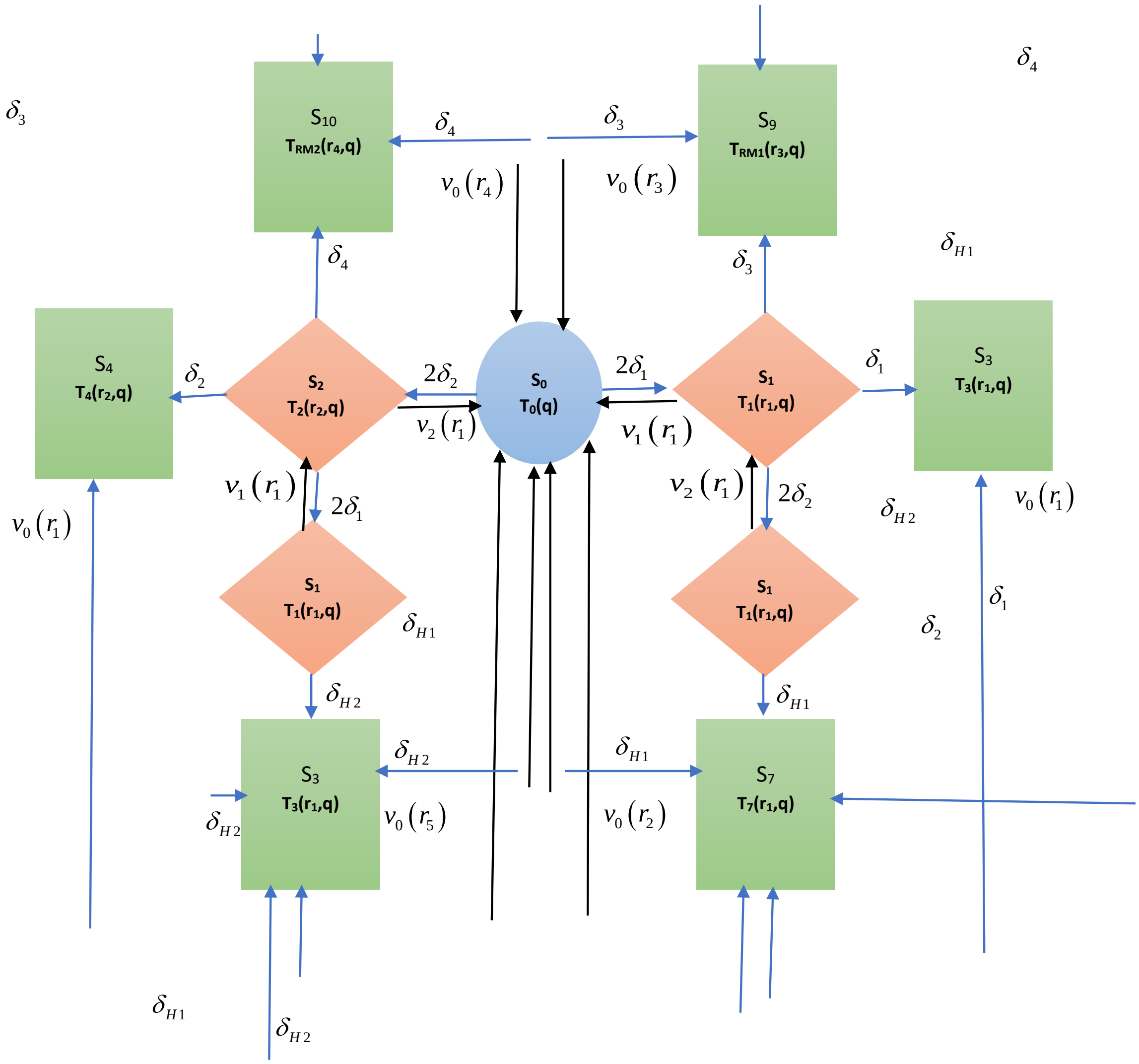


FIGURE 2
STATE TRANSITION DIAGRAM OF MODEL

- *Presentation of Models*

To create probabilistic models for systems, the technique of supplementary variable and transform of Laplace are frequently used in reliability modeling and analysis. The governing differential equations that describe the system can be made simpler using this method, which makes them simpler and easier to solve. Differential equations can be converted into algebraic equations that are simple to solve using Laplace transforms. This method enables the system's probability distribution function's Laplace transform to be derived. After obtaining the probability distribution function, initial and boundary conditions can be used to calculate the steady state probabilities. These probabilities form the foundation for the creation of reliability models, which permit the examination of the system's performance and pinpoint possible failure modes.

The following equations are obtained via Figure 2:

$$\left(\frac{\partial}{\partial q}+2\delta_1+2\delta_2+\delta_3+\delta_4+\delta_{H1}+\delta_{H2}\right)T_0(q)=\int_0^\infty v_1(r_1)T_1(r_1,q)dr_1+\int_0^\infty v_2(r_1)T_2(r_1,q)drr_1$$
$$\int_0^\infty v_0(r_1)T_3(r_1,q)dr_1+\int_0^\infty v_0(r_1)T_4(r_1,q)dr_1+\int_0^\infty v_0(r_2)T_{H1}(r_2,q)dr_2+\int_0^\infty v_0(r_5)T_{H2}(r_5,q)dr_5+$$
$$\int_0^\infty v_0(r_3)T_{RM1}(r_3,q)dr_3+\int_0^\infty v_0(r_4)T_{RM2}(r_4,q)dr_4$$
(1)

$$\left(\frac{\partial}{\partial q}+\frac{\partial}{\partial r_1}+\delta_1+2\delta_2+\delta_3+\delta_{H1}+\delta_{H2}+v_1(r_1)\right)T_1(r_1,q)=0 \tag{2}$$

$$\left(\frac{\partial}{\partial q}+\frac{\partial}{\partial r_1}+2\delta_1+\delta_2+\delta_4+\delta_{H1}+\delta_{H2}+v_2(r_1)\right)T_2(r_1,q)=0 \tag{3}$$

$$\left(\frac{\partial}{\partial q}+\frac{\partial}{\partial r_1}+v_0(r_1)\right)T_3(r_1,q)=0 \tag{4}$$

$$\left(\frac{\partial}{\partial q}+\frac{\partial}{\partial r_1}+v_0(r_1)\right)T_4(r_1,q)=0 \tag{5}$$

$$\left(\frac{\partial}{\partial q}+\frac{\partial}{\partial r_1}+\delta_2+\delta_4+\delta_{H1}+\delta_{H2}+v_2(r_1)\right)T_5(r_1,q)=0 \tag{6}$$

$$\left(\frac{\partial}{\partial q}+\frac{\partial}{\partial r_1}+\delta_1+\delta_3+\delta_{H1}+\delta_{H2}+v_1(r_1)\right)T_6(r_1,q)=0 \tag{7}$$

$$\left(\frac{\partial}{\partial q}+\frac{\partial}{\partial r_2}+v_0(r_2)\right)T_{H1}(r_2,q)=0 \tag{8}$$

$$\left(\frac{\partial}{\partial q}+\frac{\partial}{\partial r_5}+v_0\left(r_5\right)\right)T_{H2}\left(r_5,q\right)=0 \tag{9}$$

$$\left(\frac{\partial}{\partial q}+\frac{\partial}{\partial r_3}+v_0\left(r_3\right)\right)T_{RM1}\left(r_3,q\right)=0 \tag{10}$$

$$\left(\frac{\partial}{\partial q}+\frac{\partial}{\partial r_4}+v_0\left(r_4\right)\right)T_{RM2}\left(r_4,q\right)=0 \tag{11}$$

with boundary conditions below;

$$T_1\left(0,q\right)=2\delta_1 T_0\left(q\right) \tag{12}$$

$$T_2\left(0,q\right)=2\delta_2 T_0\left(q\right) \tag{13}$$

$$T_3\left(0,q\right)=\delta_1\left(T_1\left(0,q\right)+T_6\left(0,q\right)\right) \tag{14}$$

$$T_4\left(0,q\right)=\delta_1\left(T_2\left(0,q\right)+T_5\left(0,q\right)\right) \tag{15}$$

$$T_5\left(0,q\right)=2\delta_2 T_1\left(0,q\right) \tag{16}$$

$$T_6\left(0,q\right)=2\delta_1 T_2\left(0,q\right) \tag{17}$$

$$T_{H1}\left(0,q\right)=\delta_{H1}\left(T_0\left(q\right)+T_1\left(0,q\right)+T_2\left(0,q\right)+T_5\left(0,q\right)+T_6\left(0,q\right)\right) \tag{18}$$

$$T_{H2}\left(0,q\right)=\delta_{H2}\left(T_0\left(q\right)+T_1\left(0,q\right)+T_2\left(0,q\right)+T_5\left(0,q\right)+T_6\left(0,q\right)\right) \tag{19}$$

$$T_{RM1}\left(0,q\right)=\delta_3\left(T_0\left(q\right)+T_1\left(0,q\right)+T_6\left(0,q\right)\right) \tag{20}$$

$$T_{RM2}\left(0,q\right)=\delta_4\left(T_0\left(q\right)+T_2\left(0,q\right)+T_5\left(0,q\right)\right) \tag{21}$$

and the initial Condition

$$T_k\left(0\right)=\begin{cases}1, k=0\\0, otherwise\end{cases} \tag{22}$$

Applying Laplace transformations of equation (1) – (21) the following relations are obtained;

$$\left(s+2\delta_1+2\delta_2+\delta_3+\delta_4+\delta_{H1}+\delta_{H2}\right)\overline{T_0}(s)=1+\int_0^\infty v_1(r_1)\overline{T}_1(r_1,s)\,dr_1+\int_0^\infty v_2(r_1)\overline{T}_2(r_1,s)\,dr_1+$$
$$\int_0^\infty v_0(r_1)\overline{T}_3(r_1,s)\,dr_1+\int_0^\infty v_0(r_1)\overline{T}_4(r_1,s)\,dr_1+\int_0^\infty v_0(r_2)\overline{T}_{H1}(r_2,s)\,dr_2+\int_0^\infty v_0(r_5)\overline{T}_{H2}(r_5,s)\,dr_5+$$
$$\int_0^\infty v_0(r_3)\overline{T}_{RM1}(r_3,s)\,dr_3+\int_0^\infty v_0(r_4)\overline{T}_{RM2}(r_4,s)\,dr_4$$

(22)

$$\left(s+\frac{\partial}{\partial r_1}+\delta_1+2\delta_2+\delta_3+\delta_{H1}+\delta_{H2}+v_1(r_1)\right)\overline{T}_1(r_1,s)=0 \tag{23}$$

$$\left(s+\frac{\partial}{\partial r_1}+2\delta_1+\delta_2+\delta_4+\delta_{H1}+\delta_{H2}+v_2(r_1)\right)\overline{T}_2(r_1,s)=0 \tag{24}$$

$$\left(s+\frac{\partial}{\partial r_1}+v_0(r_1)\right)\overline{T}_3(r_1,s)=0 \tag{25}$$

$$\left(s+\frac{\partial}{\partial r_1}+v_0(r_1)\right)\overline{T}_4(r_1,s)=0 \tag{26}$$

$$\left(s+\frac{\partial}{\partial r_1}+\delta_2+\delta_4+\delta_{H1}+\delta_{H2}+v_2(r_1)\right)\overline{T}_5(r_1,s)=0 \tag{27}$$

$$\left(s+\frac{\partial}{\partial r_1}+\delta_1+\delta_3+\delta_{H1}+\delta_{H2}+v_1(r_1)\right)\overline{T}_6(r_1,s)=0 \tag{28}$$

$$\left(s+\frac{\partial}{\partial r_2}+v_0(r_2)\right)\overline{T}_{H1}(r_2,s)=0 \tag{29}$$

$$\left(s+\frac{\partial}{\partial r_5}+v_0(r_5)\right)\overline{T_{H2}}(r_5,s)=0 \tag{30}$$

$$\left(s+\frac{\partial}{\partial r_3}+v_0(r_3)\right)\overline{T}_{RM1}(r_3,s)=0 \tag{31}$$

$$\left(s+\frac{\partial}{\partial r_4}+v_0(r_4)\right)\overline{T_{RM2}}(r_4,s)=0 \tag{32}$$

with boundary conditions as follows**;**

$$\overline{T_1}(0,s)=2\delta_1\overline{T_0}(s) \tag{33}$$

$$\overline{T}_2(0,s)=2\delta_2\overline{T}0(s) \tag{34}$$

$$\overline{T}_3(0,s)=\delta_1\left(\overline{T}1(0,s)+\overline{T}_6(o,s)\right) \tag{35}$$

$$\overline{T}_4(0,s)=\delta_2\left(\overline{T}_2(0,s)+\overline{T}_5(o,s)\right) \tag{36}$$

$$\overline{T}_5(0,s)=2\delta_2\overline{T}_1(0,s) \tag{37}$$

$$\overline{T}_6(0,s)=2\delta_1\overline{T}_2(0,s) \tag{38}$$

$$\overline{T}_{H1}(0,s)=\delta_{H1}\left(\overline{T}_0(s)+\overline{T}_1(0,s)+\overline{T}_2(0,s)+\overline{T}_5(0,s)+\overline{T}_6(0,s)\right) \tag{39}$$

$$\overline{T}_{H2}(0,s)=\delta_{H2}\left(\overline{T}_0(s)+\overline{T}_1(0,s)+\overline{T}_2(0,s)+\overline{T}5(0,s)+\overline{T}_6(0,s)\right) \tag{40}$$

$$\overline{T}_{RM1}(0,s)=\delta_3\left(\overline{T}_0(s)+\overline{T}_1(0,s)+\overline{T}_5(0,s)\right) \tag{41}$$

$$\overline{T}_{RM2}(0,s)=\delta_4\left(\overline{T}_0(s)+\overline{T}_2(0,s)\overline{+T}_5(o,s)\right) \tag{42}$$

Solving (22) to (32) using (33) – (42) and initial conditions to have;

$$\overline{T}_0(s)=\frac{1}{W(s)} \tag{43}$$

$$\overline{T}_1(s)=\frac{2\delta_1}{W(s)}\left\{\frac{1-\overline{s}_{v_1}\left(s+\delta_{H1}+\delta_1+\delta_3+\delta_{H2}+2\delta_2\right)}{s+\delta_{H1}+\delta_1+\delta_3+\delta_{H2}+2\delta_2}\right\} \tag{44}$$

$$\overline{T}_2(s)=\frac{2\delta_2}{W(s)}\left\{\frac{1-\overline{s}_{v_2}\left(s+\delta_4+\delta_{H1}+\delta_2+\delta_{H2}+2\delta_1\right)}{s+\delta_4+\delta_{H1}+\delta_2+\delta_{H2}+2\delta_1}\right\} \tag{45}$$

$$\overline{T}_3(s)=\left(\frac{2\delta_2^2+4\delta_2^2\delta_2}{W(s)}\right)\left\{\frac{1-\overline{s}_{v_0}(s)}{s}\right\} \tag{46}$$

$$\bar{T}_4(s)=\left(\frac{2\delta_1^2+4\delta_1^2\delta_2}{W(s)}\right)\left\{\frac{1-\bar{s}_{v_0}(s)}{s}\right\} \tag{47}$$

$$\bar{T}_5(s)=\frac{4\delta_1\delta_2}{W(s)}\left\{\frac{1-\bar{s}_{v_2}\left(s+\delta_{H1}+\delta_2+\delta_{H2}+\delta_4\right)}{s+\delta_{H1}+\delta_2+\delta_{H2}+\delta_4}\right\} \tag{48}$$

$$\bar{T}_6(s)=\frac{4\delta_1\delta_2}{W(s)}\left\{\frac{1-\bar{s}_{\beta_1}\left(s+\delta_{H1}+\delta_3+\delta_{H2}+\delta_1\right)}{s+\delta_{H1}+\delta_3+\delta_{H2}+\delta_1}\right\} \tag{49}$$

$$\bar{T}_{H1}(s)=\left(\frac{\delta_{H1}+2\delta_1\delta_{H1}+2\delta_2\delta_{H1}}{W(s)}\right)\left\{\frac{1-\bar{s}_{v_0}(s)}{s}\right\} \tag{50}$$

$$\bar{T}_{H2}(s)=\left(\frac{\delta_{H2}+2\delta_1\delta_{H2}+2\delta_2\delta_{H2}}{W(s)}\right)\left\{\frac{1-\bar{s}_{v_0}(s)}{s}\right\} \tag{51}$$

$$\bar{T}_{RM1}(s)=\left(\frac{\delta_3+2\delta_1\delta_3+4\delta_1\delta_2\delta_3}{W(s)}\right)\left\{\frac{1-\bar{s}_{v_0}(s)}{s}\right\} \tag{52}$$

$$\bar{T}_{RM2}(s)=\left(\frac{\delta_4+2\delta_2\delta_4+4\delta_1\delta_2\delta_4}{W(s)}\right)\left\{\frac{1-\bar{s}_{v_0}(s)}{s}\right\} \tag{53}$$

Where W(s) is given as;

$$W(s)=\left\{s+\delta_3+\delta_{H1}+2\delta_2+\delta_4+\delta_{H2}+2\delta_1-\left(\begin{array}{l}2\delta_1\bar{s}_{\beta_1}\left(s+\delta_{H2}+\delta_3+2\delta_2+\delta_{H1}+\delta_1\right)+\\ 2\delta_2\bar{s}_{\beta_2}\left(s+\delta_4+\delta_{H2}+\delta_2+\delta_{H1}+2\delta_1\right)+\\ \left[\begin{array}{l}\left(2\delta_1^2+4\delta_1^2\delta_2\right)+\left(2\delta_2^2+4\delta_1\delta_2^2\right)+\\ \left(\delta_{H1}+2\delta_1\delta_{H1}+2\delta_2\delta_{H1}+8\delta_1\delta_2\delta_{H1}\right)+\\ \left(\delta_{H2}+2\delta_1\delta_{H2}+2\delta_2\delta_{H2}+8\delta_1\delta_2\delta_{H2}\right)+\\ \left(\delta_3+2\delta_1\delta_3+4\delta_1\delta_2\delta_3\right)+\\ \left(\delta_4+2\delta_1\delta_4+4\delta_1\delta_2\delta_4\right)\end{array}\right]\bar{s}_{\alpha_0}(s)\end{array}\right)\right\} \quad (54)$$

The entire working probability of the system is

$$\bar{T}up(s)=\left[\bar{T}_0(s)+\bar{T}_1(s)+\bar{T}_2(s)+\bar{T}_5(s)+\bar{T}_6(s)\right] \quad (55)$$

by substitution

$$\bar{T}up(s)=\frac{1}{W(s)}\left\{\begin{array}{l}1+2\delta_1\left(\dfrac{1-\bar{s}_{\beta_1}\left(s+\delta_1+2\delta_2+\delta_3+\delta_{H1}+\delta_{H2}\right)+}{s+\delta_1+2\delta_2+\delta_3+\delta_{H1}+\delta_{H2}}\right)+\\ 2\delta_2\left(\dfrac{1-\bar{s}_{\beta_2}\left(s+2\delta_1+\delta_2+\delta_4+\delta_{H1}+\delta_{H2}\right)+}{s+2\delta_1+\delta_2+\delta_4+\delta_{H1}+\delta_{H2}}\right)+\\ 4\delta_1\delta_2\left(\dfrac{1-\bar{s}_{\beta_2}\left(s+\delta_2+\delta_4+\delta_{H1}+\delta_{H2}\right)+}{s+\delta_2+\delta_4+\delta_{H1}+\delta_{H2}}\right)+\\ 4\delta_1\delta_2\left(\dfrac{1-\bar{s}_{\beta_1}\left(s+\delta_{H2}+\delta_3+\delta_{H1}+\delta_1\right)+}{s+\delta_{H2}+\delta_3+\delta_{H1}+\delta_1}\right)\end{array}\right\} \quad (56)$$

$$\bar{T}down(s)=1-\bar{T}up(s)) \quad (57)$$

- *Availability Model: Presentation and Analysis*

From (56), considering $S_{v_0}(s) = \bar{S}_{\exp[y^{\theta}+\{\log\varphi(y)\}^{\theta}]^{1/\theta}}(s) = \frac{\exp[y^{\theta}+\{\log\varphi(y)\}^{\theta}]^{1/\theta}}{s+\exp[y^{\theta}+\{\log\varphi(y)\}^{\theta}]^{1/\theta}}$, $\bar{S}_{v_1}(s) = \frac{v_1}{s+v_1}$, and $\delta_1 = 0.01$, $\delta_2 = 0.02$, $\delta_3 = 0.03$, $\delta_4 = 0.03$, $\delta_{H1} = 0.04$ and $\delta_{H2} = 0.04$ rates of repair as $1 = v_1 = v_2 = v_0 = r_1 = r_2 = r_5 = r_3 = r_4$, and inverting the Laplace to have:

$$\bar{T}up(q) = \begin{Bmatrix} 0.052649e^{-2.87072q} - 0.010186e^{-1.20122q} - 0.000109e^{-1.15618q} + 0.958120e^{-0.0016q} \\ -0.000207e^{-1.13000q} - 0.000266e^{-1.12000q} \end{Bmatrix} \quad (58)$$

For availability examination, considering passage of time $q \in [0,30]$ to have Table 1.

TABLE 1
TIME PASSAGE WITH THE CORRESPONDING AVAILABILITY

q	0	3	6	9	12	15	18	21	24	27	30
$\bar{T}up(q)$	1.0000	0.9573	0.9571	0.9567	0.9562	0.9558	0.9553	0.9549	0.9544	0.9539	0.9535

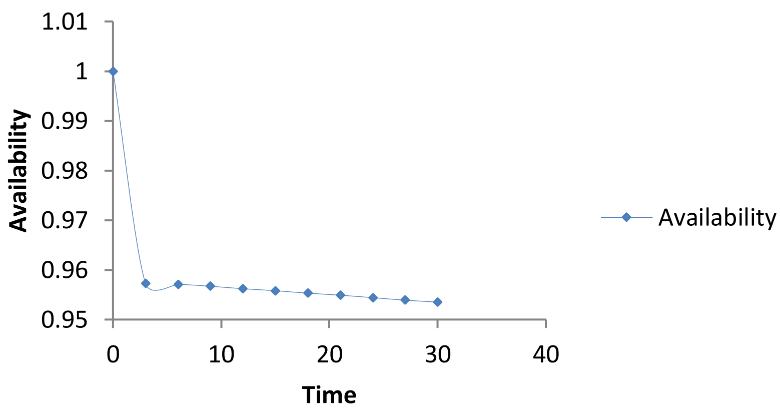


FIGURE 3
TIME PASSAGE WITH AVAILABILITY

- *Reliability Model: Presentation and Analysis*

Following the similar procedure in 4.1, $v_1(r_1)$, $v_2(r_1)$ and v_0 assigned to zero, and inverting the Laplace, the reliability model of the system is

$$R(q) = \left\{-5.082323e^{-0.18000q} + 6e^{-0.16000q} + 0.026666e^{-0.06000q} + 0.035657e^{-0.04000q} + 0.02e^{-0.02000q}\right\}$$
(59)

For reliability examination, considering passage of time $q \in [0,30]$ to have the following Table 2.

TABLE 2
TIME PASSAGE WITH THE CORRESPONDING RELIABILITY

q	0	3	6	9	12	15	18	21	24	27	30
$R(q)$	1.0000	0.6578	0.4299	0.2796	0.1811	0.1169	0.0753	0.0483	0.0310	0.0198	0.0127

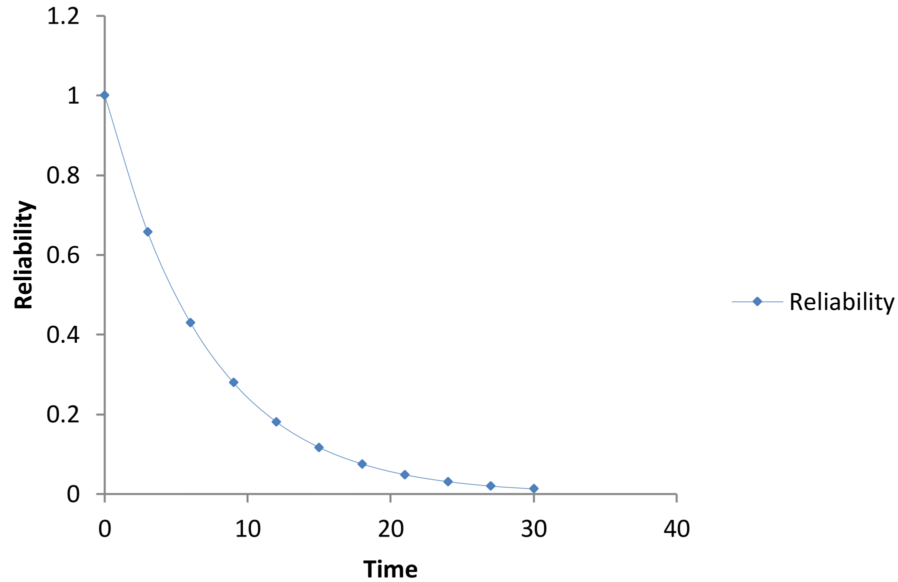


FIGURE 4
TIME PASSAGE WITH RELIABILITY

- *Mean time to failure Model: Presentation and Analysis*

By considering $v_1(r_1)$, $v_2(r_1)$ and v_0 to zero in equation (56) to have the MTTF as follows:

$$MTTF = \lim_{s\to 0} \overline{T}up(s) = \frac{1}{2\delta_1 + 2\delta_2 + \delta_3 + \delta_4 + \delta_{H1} + \delta_{H2}} \left\{ \begin{array}{l} 1 + \dfrac{2\delta_1}{\delta_1 + 2\delta_2 + \delta_3 + \delta_{H1} + \delta_{H2}} + \\ \dfrac{2\delta_2}{2\delta_1 + \delta_2 + \delta_4 + \delta_{H1} + \delta_{H2}} + \\ \dfrac{4\delta_1\delta_2}{\delta_2 + \delta_4 + \delta_{H1} + \delta_{H2}} + \\ \dfrac{4\delta_1\delta_2}{\delta_1 + \delta_3 + \delta_{H1} + \delta_{H2}} \end{array} \right\} \quad (60)$$

Fixing $\delta_1 = 0.01$, $\delta_2 = 0.02$, $\delta_3 = 0.03$, $\delta_4 = 0.03$, $\delta_{H1} = 0.04$ and $\delta_{H2} = 0.04$ in (60) varying δ_k, $k = 1, 2, 3, 4, H1, H2$ in (60) to obtained Table e for MTTF

TABLE 3
EFFECT OF RATE OF FAILURE ON MTTF

δ_k	MTTF					
	(a)	(b)	(c)	(d)	(e)	(f)
0.01	7.0224	7.1798	7.9093	8.0368	8.8474	8.8474
0.02	6.7963	7.0224	7.4390	7.4949	8.1434	8.1434
0.03	6.5811	6.8394	7.0224	7.0224	7.5420	7.5420
0.04	6.3749	6.6441	6.6505	6.6065	7.0224	7.0224
0.05	6.1774	6.4447	6.3165	6.2377	6.5691	6.5691
0.06	5.9886	6.2465	6.0148	5.9082	6.1702	6.1702
0.07	5.8084	6.0527	5.7409	5.6120	5.8166	5.8166
0.08	5.6367	5.8651	5.4910	5.3444	5.5009	5.5009
0.09	5.4733	5.6848	5.2622	5.1013	5.2175	5.2175

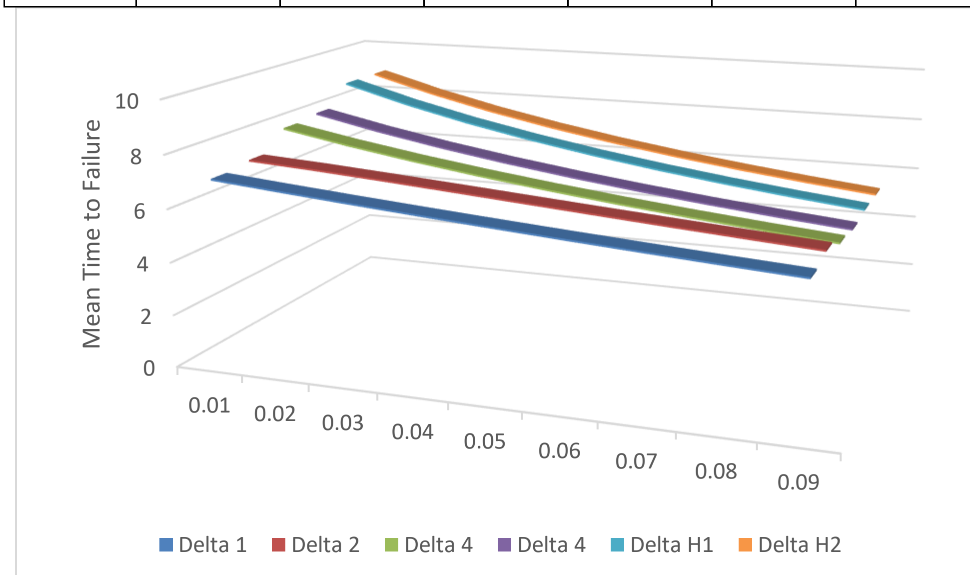


FIGURE 5
IMPACT OF RATE OF FAILURES ON MTTF

- *Cost Model: Presentation and Analysis*

The expression for the profit anticipation accumulated in $[0, q)$

$$E_p(q) = G_1 \int_0^t T_{up}(q)\, dq - G_2 q \tag{61}$$

From (56), the subsequent equation (62) follows;

$$E_p(q) = G_1 \left\{ \begin{array}{l} -0.018340e^{-2.87072q} + 0.008479e^{-1.20122q} + 0.000094e^{-1.15618q} - 598.072776e^{-0.00016q} \\ +0.000183e^{-1.13000q} + 0.000237e^{-1.12000q} + 5985.0821 \end{array} \right\} - G_2(q) \quad (62)$$

Assuming G_1= 1 and G_2= 0.1, 0.2..., 0.5, passage of time $q \in [0, 30]$ to have Table 4 below

TABLE 4
PASSAGE OF TIME WITH THE CORRESPONDING PROFIT

t	$E_p(t)$				
	(a)	(b)	(c)	(d)	(e)
0	0	0	0	0	0
1	0.8690	0.7690	0.6690	0.5690	0.4690
2	1.7260	1.5260	1.3260	1.1260	0.9260
3	2.5832	2.2832	1.9832	1.6832	1.3832
4	3.4406	3.0406	2.6406	2.2406	1.8406
5	4.2980	3.7980	3.2980	2.7980	2.2980
6	5.1552	4.5552	3.9552	3.3552	2.7552
7	6.0124	5.3124	4.6124	3.9124	3.2124
8	6.8693	6.0693	5.2693	4.4693	3.6693
9	7.7262	6.8262	5.9262	5.0262	4.1262
10	8.5828	7.5828	6.5828	5.5828	4.5828

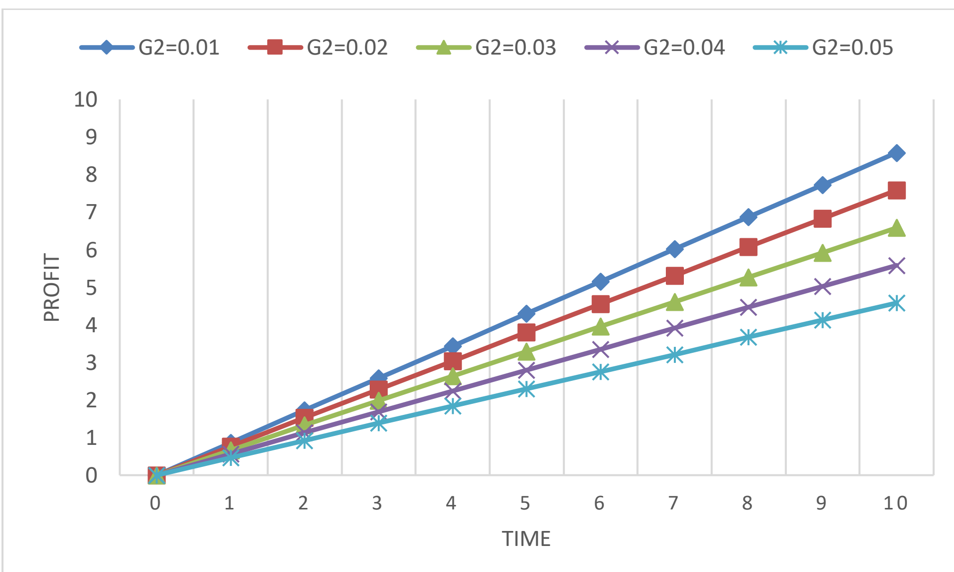
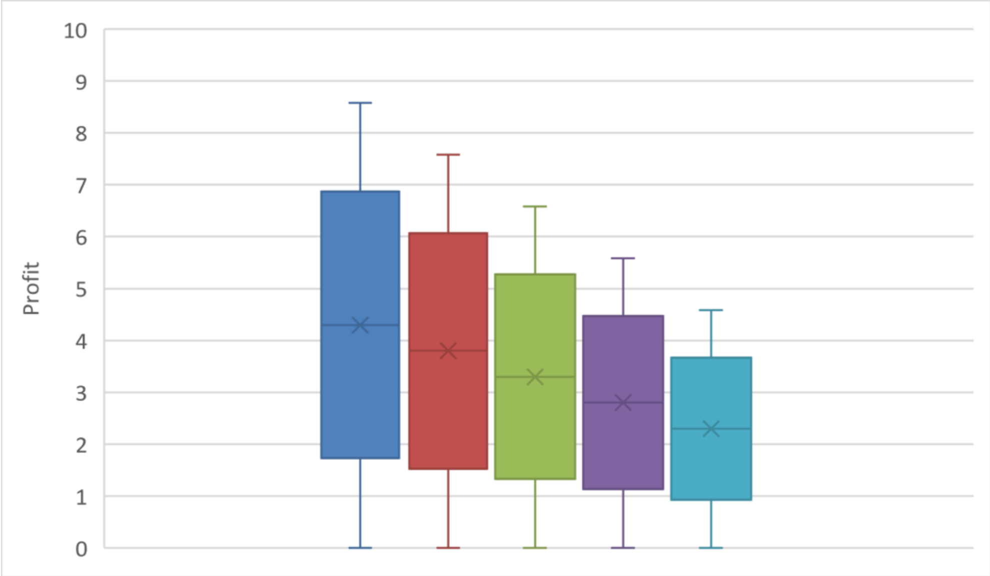


FIGURE 6
TIME PASSAGE WITH THE CORRESPONDING PROFIT



G_2

FIGURE 8

Time passage with corresponding Profit $G_2 \in \{0.01, 0.02, 0.03, 0.04, 0.05\}$

RESULTS DISCUSSION

The simulation depicted in Figure 3 has shown that availability declines over time. The figure clearly shows that the equipment's availability was higher in earlier times in $q \in [0, 30]$. Similarly, Figure 4 depict the reliability of the system with respect to time. From the figure, it is observed that reliability decreases at time q increases from 0 to 30. However, reliability is higher in the time interval $q \in [0, 5]$. Figures 3 and 4 show that the system's availability and reliability can be increased, among other things, by adding more standby units, carrying out excellent repairs when there are partial failures, replacing the malfunctioning subsystem with a new one in the scenario of a complete breakdown, performing periodic examinations and preventive maintenance, and assigning more restoration machines. A simulation showing the mean time to failure in connection with the rate of failure δ_k is shown in Figure 5. The figure unequivocally shows that the mean time to failure (MTTF) declines as the breakdown rate δ_k rises. As δ_k increases, it led to decrease in MTTF which will culminate in reduction of lifespan of the system. It is advantageous to use fault-tolerant components to extend the system's mean time to failure (MTTF) and lifespan. The relationship between profit and passing time q is shown in Figure 6 for $G_2 \in \{0.01, 0.02, 0.03, 0.04, 0.05\}$. From the figure, the expected profit decreases as time q increases for any value of G_2. However, the expected profit is higher with smaller value of G_2.

Similar observation can be seen in Figure 8. Figure 8 shows a boxplot that shows the anticipated profit in comparison to time for different service cost G_2. In this figure, it's evident that the expected profit decreases as the service cost value increases. The expected profit can be enhanced by adopting the suggestion provided above. Figure 8 uses a boxplot to visually represent the relationship between expected profit and time for different service cost scenarios. This graphical representation helps us identify a clear trend: the expected profit steadily declines as the service cost rises. This important realization is succinctly conveyed in the boxplot. Decision-makers must comprehend the decreasing trend in expected profit as service costs increase. It emphasizes how important it is to control service costs well and possibly cut them in order to sustain or boost profitability. This is especially crucial if you want to maximize your financial performance. It is evident that there is a negative correlation between expected profit and service cost, indicating that improving profitability will require action. Thankfully, the figure indicates that there may be tactics or recommendations that can be used to raise the anticipated profit. By putting these suggestions into practice, the negative effects of rising service costs may be lessened and profitability may rise. Together with the practical recommendations, the insights presented in Figure 8 provide a useful tool for decision-making and for guiding the company toward a more lucrative and sustainable future. Stakeholders must take these findings into account and apply them to their strategic planning and management procedures.

Fixing the values of failure and repair rates $\delta_1 = 0.01$, $\delta_2 = 0.02$, $\delta_3 = 0.03$, $\delta_4 = 0.03$, $\delta_{H1} = 0.04$ and $\delta_{H2} = 0.04$ and repair rates $v_1(r_1) = v_2(r_1) = v_0(r) = r_1 = r_2 = r_3 = r_4 = r_5 = 1$, Table 1 displayed the availability for different values time. According to the table, availability declines as time increases. Considering the repairs $v_1(x)$, $v_2(x)$ and v_0 in equation (56) to zero and fixing $\delta_1 = 0.01$, $\delta_2 = 0.02$, $\delta_3 = 0.03$, $\delta_4 = 0.03$, $\delta_{H1} = 0.04$ and $\delta_{H2} = 0.04$, Table displayed the reliability for different values time. From the table, reliability declined with increase in the time.

The following items are employed for the analysis of MTTF:

(a) $\delta_2 = 0.02$, $\delta_3 = 0.03$, $\delta_4 = 0.03$, $\delta_{H1} = 0.04$, $\delta_{H2} = 0.04$ varying δ_1 from 0.01 to 0.09

(b) $\delta_1 = 0.01$, $\delta_3 = 0.03$, $\delta_4 = 0.03$, $\delta_{H1} = 0.04$, $\delta_{H2} = 0.04$ varying δ_2 from 0.01 to 0.09

(c) $\delta_1 = 0.01$, $\delta_2 = 0.02$, $\delta_4 = 0.03$, $\delta_{H1} = 0.04$, $\delta_{H2} = 0.04$ varying δ_3 from 0.01 to 0.09

(d) $\delta_1 = 0.01$, $\delta_2 = 0.02$, $\delta_3 = 0.03$, $\delta_{H1} = 0.04$, $\delta_{H2} = 0.04$ varying δ_4 from 0.01 to 0.09

(e) $\delta_1 = 0.01$, $\delta_2 = 0.02$, $\delta_3 = 0.03$, $\delta_4 = 0.03$, $\delta_{H2} = 0.04$ varying δ_{H1} from 0.01 to 0.09

(f) $\delta_1 = 0.01$, $\delta_2 = 0.02$, $\delta_3 = 0.03$, $\delta_4 = 0.03$, $\delta_{H1} = 0.04$ and varying δ_{H2} from 0.01 to 0.09

Table 3 illustrate the MTTF concerning the rate of failure. From the illustration, the MTTF decreases as the failure rates δ_k increase.

The following components are utilized in the analysis of profit.: $G_2 \in [0.01, 0.05]$ and varying $q \in [0,10]$

Table 4 presents the outcomes of expected profit concerning the passage of time. The table clearly shows that expected profit rises as service cost decreases.

CONCLUSION

In conclusion, this paper presents a comprehensive analysis of a serial system managed by human operators and repair machines, utilizing the Gumbel-Hougaard family copula for reliability and performance assessment. The study examines the system's behavior under two different failure types and formulates explicit expressions for reliability and various performance metrics, including sensitivity, availability, cost function or profit, and mean time to failure. Numerical validation of these expressions through tables and figures confirms the benefits of periodic copula-based repairs in improving system reliability and performance. The research highlights the critical role of repair machines in collaboration with human operators to enhance system performance and reliability. System failures can significantly impact production performance and may lead to severe consequences. However, the introduction of copula-based repair machines demonstrates a substantial contribution to improving overall system efficiency and reliability.

The study's findings have practical implications for system engineers and maintenance managers, recommending the adoption of multi-dimensional copula repair with fault tolerance factor to improve system performance and efficiency. This understanding can result in better-informed decision-making when it comes to designing and maintaining intricate repairable systems. To expand upon this work, future research could involve increasing the number of units in each subsystem and implementing robots and advanced repair machines to further enhance system reliability and performance. The exploration of these aspects would provide deeper insights into the behavior of complex systems under different conditions and parameter values. In conclusion, this investigation sheds light on the intricacies of repairable systems and offers valuable insights into their reliability, availability, mean time to failure, sensitivity, and profit optimization. The study's practical guidance can assist decision-makers in enhancing system performance, ultimately contributing to increased productivity and efficiency across various industries.

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