Performance and Cost Assessment of a Small Solar Photovoltaic System Using Gumbel-Hauggaard Family Copula Analysis

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Abstract

The main objective of the present study is to analyze the availability of solar photovoltaic system. The solar photovoltaic system in this paper is simple one consisting of four subsystems namely, solar panel subsystem, charge controller subsystem, batteries subsystem and inverter subsystem. Through the schematic diagram of state of the system, availability model is formulated and Chapman-Kolmogorov differential equations are developed and solved using Gumbel Hauggaard family Copula technique. The numerical values for availability, reliability, mean time to failure (MTTF), cost analysis as well as sensitivity analysis are presented. The effects of failure rates to various solar photovoltaic subsystems were developed.

Keywords: Solar panels, Photovoltaic, Batteries, Copula, Availability

1. Introduction

Reliability modeling and performance evaluation of solar photovoltaic system using Gumbel–Hougaard family copula was studied by Maihulla et al. (2021). Review of failures of photovoltaic modules was carried out by Köntges M (2014). Long-term field test of solar PV power generation using one-axis 3-position sun tracker was analysed by Huang B J et al. (2011). In (2003) the partial shadowing of photovoltaic arrays with different system configurations was studied by Woyte A et al. Nishioka K. et al. (2003) investigated Field-test analysis of PV system output characteristics focusing on module temperature. Kinsey G S.(2015) analyzed the Spectrum sensitivity, energy yield, and revenue prediction of PV modules. Xing Zheng. (2015) carried out a research titled the Modelling dependence structures of soil shear strength data with bivariate copulas and applications to geotechnical reliability analysis. Mao-X. (2020) study the subset simulation for efficient slope reliability analysis involving copula based cross-correlated random fields. Yusuf I. et al. (2020) study the reliability modelling and analysis of client–server system using Gumbel–Hougaard family copula. V. V singh and Monika G (2021) study the Reliability analysis of (n) clients system under star topology and copula linguistic approach. Adebayo et al. (2018), study The Status Quo of Rural and Renewable Energy Development in Liberia: Policy and Implementation. The study regarding the Accurate Sizing of Residential Stand-Alone Photovoltaic Systems Considering System Reliability was carried out by Eduardo et al. (2020) Also The Motivation for Incorporation of Microgrid Technology in Rooftop Solar Photovoltaic Deployment to Enhance Energy Economics was a research conducted by M. Rengasamy et al. (2020). J. A. Salah et al(2019) Designed a hybrid solar photovoltaic system for Gollis University's administrative block, Somaliland. Then Reliability analysis of photovoltaic system is demonstrated by I. M. Saleh (1995). R. Uswarman (2021) discussed the Reliability Evaluation of Rooftop Solar Photovoltaic Using Coherent Threshold Systems. Adebayo et al. (2018) studied The Drivers and Barriers of Renewable Energy Applications and Development in Uganda. Wang et al. (2017) established driving factors of energy related carbon emissions using the extended STIRPAT model based on
The study of Reliability Analysis on Complex Systems with Common Cause Failures was discussed by E. Patelli et al. (2017). A. Sayeed et al. (2019) studied the Reliability, Availability and Maintainability Analysis for Grid-Connected Solar Photovoltaic Systems. S. Baschel et al. (2018) discuss the Impact of Component Reliability on Large Scale Photovoltaic Systems’ Performance. Markov process reliability model for photovoltaic module encapsulation failures was elaborated by L. Cristaldi, et al. (2015). The study pertaining accurate Sizing of Residential Stand-Alone Photovoltaic Systems Considering System Reliability was carried out by E. Quiles (2020). Also Feasibility study of renewable energy-based microgrid system in Somaliland’s urban centers is a research carried out by A. M. Abdilahi et al. (2014). Dynamic performance evaluation of photovoltaic power plant by stochastic hybrid fault tree automaton model studied by et al. Chiacchio, F. (2018). Reliability, maintainability and sensitivity analysis of physical processing unit of sewage treatment plant is a research conducted by Goyal, D. et al. (2019). Reliability Analysis of Distribution Systems with Photovoltaic Generation Using a Power Flow Simulator and a Parallel Monte Carlo Approach was studied by Juan A. Martinez-Velasco and Gerardo Guerra (2016). In 2016 the Reliability Analyses on Distribution Networks with Dispersed Generation was also studied by Ferreira, H. et al. (2016). P. Zhang et al. (2013) discussed the Reliability assessment of photovoltaic power systems. Also Copula-Based Slope Reliability Analysis Using the Failure Domain Defined by the \( g \)-Line by X. Xu et al. (2016). Singh et al. (2019) studied the Cost assessment of complex repairable system consisting two subsystems in series configuration using Gumbel Hougaard family copula.

To address the concerns mentioned in earlier work on grid-connected PV system reliability, this study presents a full thorough Copula analysis for all sub-assemblies of grid-connected solar PV systems with a low dependability grid, taking failure specifics and repair intervals into consideration (period of identification and replacement of the PV system). Furthermore, the goal of this work is to explain the dependability of each sub-assembly of grid-connected PV systems. The scope of this study has also been expanded to determine the optimum probability density function for each solar-PV device subassembly's failure rate.

Because data for the PV system is not readily available, the current work uses a reliability modeling technique to investigate the PV system's overall performance. In this work, we provide a novel solar system model that consists of four subsystems: panel, inverter, battery bank, and control charger. The units in each subsystem are considered to have exponential failure and repair times, according to Ismail et al. (2021).

The authors looked at a variety of systems that are related to solar photovoltaic systems. Typically, they haven't paid much attention to their operations when using k-out-of-n: systems, which can be seen in a variety of real-world scenarios. However, in many locations, such as banks, factories, schools, and other communication channels, we see redundancy in subsystems, particularly solar panels, there is provision for another panel to continue to function even when others fail. We have examined this home based modest scaled photovoltaic, with redundancy in the solar panels and batteries alone, in light of this outstanding construction. The setup is series-parallel with a k-out-
of-n: G operation scheme. A flawless state, a degraded state, and a failing state are the three states of the system. When there are k excellent states in the system, the entire system is functioning, but when there are less than k good clients, the system is on the verge of failing completely. The failure of the primary panel is considered as a partial failure, whereas the failure of the redundant ones is treated as a full failure before the primary ones are repaired. Charge controller and inverter failures are total system failures, copula repair is used to quickly restore the system. For varied values of failure and repair rates, the system was evaluated using the supplementary variable technique, and various reliability indices were produced.

![Figure 1: Block Diagram for the System](image)

2. **Table 1: STATE DESCRIPTION AND ASSUMPTIONS**

| State | Description |
|-------|-------------|
| S₀    | Initial state, Unit A₁, B₁, C₁ and D₁ are working. Unit A₂, A₃ and C₂ are on Standby mode hotly. And the system is in operational condition. |
| S₁    | In this state, the unit A₁ failed and under repair. And the elapsed repair time is (x, t). While the units A₂, B₁, C₁, and D₁, are on operation and the units A₃ and C₂ are on standby. |
| S2 | In this state, the unit A₁ and A₂ failed and under repair. And the elapsed repair time is (x, t). While the units A₂, B₁, C₁, and D₁, are on operation and the units A₃ and C₂ are on standby. |
|----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| S3 | The units A₁ and C₁ has failed. While the units A₂, B₁, C₂, and D₁, are on operation. While A₂ and A₃ are on standby.                                                                                     |
| S4 | In this state, the unit A₁ and A₂ from subsystem 1. And C₁ from subsystem 3 are have failed and are under repair. While the units A₃, from subsystem 1, B₁, from subsystem2 C₂ from subsystem 3 and D₁ from subsystem 4 are on operations. |
| S5 | The state S₅ is complete failed state due to the failure of subsystem 2.                                                                                                                                   |
| S6 | The state S₆ is complete failed state due to the failure of subsystem 1.                                                                                                                                   |
| S7 | The state S₇ is complete failed state due to the failure of subsystem 3.                                                                                                                                   |
| S8 | The state S₈ is complete failed state due to the failure of subsystem 4.                                                                                                                                   |

**ASSUMPTIONS**

The following assumption are taken throughout the discussion of the model:

1) Initially, both subsystems are in good working condition.

2) One unit from subsystem, subsystem 2, subsystem 3 and subsystem 4 in consecutive are necessary for operational mode.

3) The system will be inoperative if three units from subsystem 1 failed. Also if two units from sub system 3 failed.

4) The system will also be inoperative if one unit failed from either of subsystem 2 and 4 respectively.

5) Failed unit of the system can be repaired when it is inoperative or failed state.

6) Copula repair follows a total failure of a unit in subsystem.

7) It is assumed that a repaired system by copula works like a new system and no damage appears during repair.

8) As soon as the failed the failed unit gets repaired, it is ready to perform the task.

3. **NOTATIONS**

s \( \text{Laplace transform variable for all expressions.} \)
t  Time variable on a time scale.

$\Omega_1$  Failure rate of the unit in subsystem 1

$\Omega_2$  Failure rate of the unit in subsystem 2

$\Omega_3$  Failure rate of the unit in subsystem 3

$\Omega_4$  Failure rate of the unit in subsystem 4

$\omega_1(x)$  Repair of the failed unit in subsystem 1

$\omega_2(y)$  Repair of the failed unit in subsystem 2

$\omega_3(z)$  Repair of the failed unit in subsystem 3

$\omega_4(k)$  Repair of the failed unit in subsystem 4

$\Theta(x)$  Copula repair of full failure of unit in subsystem 1

$\Theta(y)$  Copula repair of full failure of unit in subsystem 2

$\Theta(z)$  Copula repair of full failure of unit in subsystem 3

$\Theta(k)$  Copula repair of full failure of unit in subsystem 4
FORMULATION AND SOLUTION OF MATHEMATICAL MODEL

By the probability of considerations and continuity of arguments, the following set of difference-differential equations are associated with the above mathematical model.

\[
\frac{d}{dt} + \varphi_1 + \varphi_2 + \varphi_3 + \varphi_4 \int_0^\infty \omega_1 P_1(x,t) dx + \int_0^\infty \theta(y) P_4(y,t) dy + \]

Figure 2: System’s Transition Diagram
\[\int_0^\infty \omega_3 P_5(z,t)dz + \int_0^\infty \Theta(k) P_5(k,t)dk + \int_0^\infty \Theta(x)(m) P_3(x,t)dx + \int_0^\infty \Theta(z) P_6(z,t)dz\tag{1}\]

\[\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + Q_1 + Q_3 + \omega_1 P_1(x,t)= 0\tag{2}\]

\[\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + Q_1 + Q_3 + \omega_1 P_2(x,t)= 0\tag{3}\]

\[\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + Q_1 + \Theta(x) P_3(x,t)= 0\tag{4}\]

\[\frac{\partial}{\partial t} + \frac{\partial}{\partial y} + \Theta(y) P_4(y,t)= 0\tag{5}\]

\[\frac{\partial}{\partial t} + \frac{\partial}{\partial z} + Q_1 + Q_3 + \omega_3 P_5(y,t)= 0\tag{6}\]

\[\frac{\partial}{\partial t} + \frac{\partial}{\partial z} + \Theta(z) P_6(z,t)= 0\tag{7}\]

\[\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + Q_3 + 2\omega_1 P_7(x,t)= 0\tag{8}\]

\[\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + Q_1 + \omega_3 P_8(x,t)= 0\tag{9}\]

\[\frac{\partial}{\partial t} + \frac{\partial}{\partial k} + \Theta(k) P_9(k,t)= 0\tag{10}\]

Boundary conditions

\[P_1(0,t) = Q_1 P_0(t)\tag{11}\]

\[P_2(0,t) = Q_2^2 P_0(t)\tag{12}\]

\[P_3(0,t) = (Q_1^3 + Q_2^2 Q_3) P_0(t)\tag{13}\]

\[P_4(0,t) = Q_2 P_0(t)\tag{14}\]

\[P_5(0,t) = Q_3 P_0(t)\tag{15}\]

\[P_6(0,t) = Q_3^2 P_0(t)\tag{16}\]

\[P_7(0,t) = 2Q_1 Q_3 P_0(t)\tag{17}\]

\[P_8(0,t) = Q_1^3 Q_3 P_0(t)\tag{18}\]

\[P_9(0,t) = Q_4 P_0(t)\tag{19}\]

Initial condition \(P_0(t) = 1\) and other transition probability at \(t=0\) are zero \(\tag{20}\)

Taking Laplace transformation of equation (1) – (19) with the help of (20), one can obtain

\[[s + Q_1 + Q_2 + Q_3 + Q_4]\bar{P}_0(t) = \int_0^\infty \omega_1 \bar{P}_1(x,s)dx + \int_0^\infty \Theta(y) \bar{P}_4(y,s)dy + \]
\[
\int_0^\infty \omega_3 P_5(z,s)dz + \int_0^\infty \Theta(k)P_3(k,s)dk + \int_0^\infty \Theta(x)(m)P_3(x,s)dx + \int_0^\infty \Theta(z)P_6(z,s)dz
\]  
(21)

\[
(s + \frac{\partial}{\partial x} + Q_1 + Q_3 + \omega_1)\bar{P_1}(x,t) = 0
\]  
(22)

\[
(s + \frac{\partial}{\partial x} + Q_1 + Q_3 + \omega_1)\bar{P_2}(x,s) = 0
\]  
(23)

\[
(s + \frac{\partial}{\partial x} + \Theta(x))\bar{P_3}(x,s) = 0
\]  
(24)

\[
(s + \frac{\partial}{\partial y} + \Theta(y))\bar{P_4}(y,s) = 0
\]  
(25)

\[
(s + \frac{\partial}{\partial z} + Q_1 + Q_3 + \omega_3)\bar{P_5}(y,s) = 0
\]  
(26)

\[
(s + \frac{\partial}{\partial z} + \Theta(z))\bar{P_6}(z,s) = 0
\]  
(27)

\[
(s + \frac{\partial}{\partial x} + Q_3 + 2\omega_1)\bar{P_7}(x,s) = 0
\]  
(28)

\[
(s + \frac{\partial}{\partial x} + Q_1 + \omega_3)\bar{P_8}(x,s) = 0
\]  
(29)

\[
(s + \frac{\partial}{\partial k} + \Theta(k))\bar{P_9}(k,s) = 0
\]  
(30)

Boundary conditions

\[
\bar{P_1}(0,s) = Q_1 \bar{P_0}(s)
\]  
(31)

\[
\bar{P_2}(0,s) = Q_1^2 \bar{P_0}(s)
\]  
(32)

\[
\bar{P_3}(0,s) = (Q_1^3 + Q_1^3 Q_3)\bar{P_0}(s)
\]  
(33)

\[
\bar{P_4}(0,s) = Q_2 \bar{P_0}(s)
\]  
(34)

\[
\bar{P_5}(0,s) = Q_3 \bar{P_0}(s)
\]  
(35)

\[
\bar{P_6}(0,s) = Q_2 Q_3 \bar{P_0}(s)
\]  
(36)

\[
\bar{P_7}(0,s) = 2Q_1 Q_3 \bar{P_0}(s)
\]  
(37)

\[
\bar{P_8}(0,s) = Q_1^3 Q_3 \bar{P_0}(s)
\]  
(38)

\[
\bar{P_9}(0,s) = Q_4 \bar{P_0}(s)
\]  
(39)

Solving equation (22) to (30) with the help of boundary condition (31) to (39) and applying the below shifting properties of Laplace.

\[
\int_0^\infty [e^{-sx} \cdot e^{-\int_0^x f(x)dx}]dx = L \left\{ \frac{1 - \frac{\delta f(x)}{s}}{s} \right\} = \frac{1 - \frac{\delta f(x)}{s}}{s}
\]  
(40)
\[ \int_0^\infty [e^{-sx} \cdot f(x) e^{-\int_0^x f(x)dx}]dx = L\{\bar{S}_f(x)\} = \bar{S}_f(s) \]  

(41)

\[ \bar{P}_1(S) = Q_1 \left\{ \frac{1-\tilde{s}_{\omega_2}(s+\varphi_1+\varphi_3)}{s+\varphi_1+\varphi_3} \right\} \bar{P}_0(s) \]  

(42)

\[ \bar{P}_2(S) = Q_1^2 \left\{ \frac{1-\tilde{s}_{\omega_1}(s+\varphi_1+\varphi_3)}{s+\varphi_1+\varphi_3} \right\} \bar{P}_0(s) \]  

(43)

\[ \bar{P}_3(S) = (Q_1^3 + Q_1^2 \varphi_3) \left\{ \frac{1-\tilde{s}_0(s)}{s} \right\} \bar{P}_0(s) \]  

(44)

\[ \bar{P}_4(S) = Q_2 \left\{ \frac{1-\tilde{s}_0(S)}{s} \right\} \bar{P}_0(s) \]  

(45)

\[ \bar{P}_5(S) = Q_3 \left\{ \frac{1-\tilde{s}_{\omega_3}(s+\varphi_1+\varphi_3)}{s+\varphi_1+\varphi_3} \right\} \bar{P}_0(s) \]  

(46)

\[ \bar{P}_6(S) = Q_3^2 \left\{ \frac{1-\tilde{s}_0(S)}{s} \right\} \bar{P}_0(s) \]  

(47)

\[ \bar{P}_7(S) = 2Q_1Q_3 \left\{ \frac{1-\tilde{s}_{2\omega_1}(s+\varphi_1)}{s+\varphi_1} \right\} \bar{P}_0(s) \]  

(48)

\[ \bar{P}_8(S) = Q_1^2 Q_3 \left\{ \frac{1-\tilde{s}_{\omega_3}(s+\varphi_1+\varphi_3)}{s+\varphi_1+\varphi_3} \right\} \bar{P}_0(s) \]  

(49)

\[ \bar{P}_9(S) = Q_4 \left\{ \frac{1-\tilde{s}_0(S)}{s} \right\} \bar{P}_0(s) \]  

(50)

\[ \bar{P}_0(S) = \frac{1}{D(S)} \]  

(51)

\[ \Rightarrow \bar{P}_0(S) = \frac{1}{D(S)} \]  

(52)

\[ \bar{P}_{up}(S) = \bar{P}_0(S) + \bar{P}_1(S) + \bar{P}_2(S) + \bar{P}_5(S) + \bar{P}_7(S) + \bar{P}_8(S) \]  

(53)

\[ \bar{P}_{down}(S) = 1 - \bar{P}_{up}(S) \]  

(54)

\[ \bar{P}_{up}(S) = \left[ 1 + Q_1 \left\{ \frac{1-\tilde{s}_{\omega_1}(s+\varphi_1+\varphi_3)}{s+\varphi_1+\varphi_3} \right\} + Q_1^2 \left\{ \frac{1-\tilde{s}_{\omega_1}(s+\varphi_1+\varphi_3)}{s+\varphi_1+\varphi_3} \right\} + Q_3 \left\{ \frac{1-\tilde{s}_{\omega_3}(s+\varphi_1+\varphi_3)}{s+\varphi_1+\varphi_3} \right\} + \right. \]  

\[ 2Q_1Q_3 \left\{ \frac{1-\tilde{s}_{2\omega_1}(s+\varphi_1)}{s+\varphi_1} \right\} + Q_1^2 Q_3 \left\{ \frac{1-\tilde{s}_{\omega_3}(s+\varphi_1+\varphi_3)}{s+\varphi_1+\varphi_3} \right\} \]  

\[ \left. \right\} \bar{P}_0(s) \]  

(55)
4. Formulation and Analysis of System Availability

Taking $S_{\alpha_0}(s) = \int \exp \left[ x^\theta \{ \log \phi(x) \}^{\theta/\phi} \right] (s) = \frac{\exp \left[ x^\theta \{ \log \phi(x) \}^{\theta/\phi} \right]}{s + \exp \left[ x^\theta \{ \log \phi(x) \}^{\theta/\phi} \right]} \phi(s) = \frac{\phi}{s + \phi}$ but $\phi = 1$ and $\rho_1 = 0.001, \rho_2 = 0.002, \rho_3 = 0.003, \rho_4 = 0.004$

And repair rates $\Theta(x) = \Theta(y) = \Theta(z) = \Theta(k) = \omega_1(x) = \omega_1(y) = \omega_1(z) = \omega_1(k) = 1$ in equation (55),

and applying the inverse Laplace transform to (55), the expression for system availability is

$$P_{up}(t) = \{ 0.00002208861717 e^{-2.71836026 t} + 0.0002090989911 e^{-1.000779179 t} - 0.00009109003812 e^{-1.000320873 t} + 0.9997779215 e^{-0.000539920997 t} - 0.000000072008791910 e^{-1.00010000 t} + 0.00000000900212922210 e^{-2.000030000 t} \}$$

(56)

Taking $t = 0, 10, \ldots, 100$, availability of the system is obtained and presented in Table 1 below

| Time (in days) | Availability $P_{up}(t)$ |
|---------------|--------------------------|
| 0             | 1.00000                  |
| 10            | 0.99439                  |
| 20            | 0.98904                  |
| 30            | 0.98371                  |
| 40            | 0.97842                  |
| 50            | 0.97315                  |
| 60            | 0.96791                  |
| 70            | 0.96270                  |
| 80            | 0.95751                  |
| 90            | 0.95236                  |
| 100           | 0.94723                  |

Figure 3. Availability as function of time
b. Reliability analysis

Taking all repair rate $\Theta(x) = \Theta(y) = \Theta(z) = \Theta(k) = \omega_1(x) = \omega_1(y) = \omega_1(z) = \omega_1(k) = 0$ and for same values of failure rate as $\varphi_1 = 0.0001, \varphi_2 = 0.0002, \varphi_3 = 0.0003, \varphi_4 = 0.0004$

And then taking inverse Laplace transform, one may have the expression for reliability for the system. Expression for reliability of the system is given as;

\[
\text{Table 3. Variation of Reliability with respect to time}
\]

| Time(t) | Reliability R(t) |
|---------|------------------|
| 0       | 1.00000          |
| 10      | 0.99204          |
| 20      | 0.98415          |
| 30      | 0.97633          |
| 40      | 0.96858          |
| 50      | 0.96090          |
| 60      | 0.95329          |
| 70      | 0.94575          |
| 80      | 0.93828          |
| 90      | 0.93087          |
| 100     | 0.92353          |
c. Mean Time to Failure (MTTF) analysis

Taking all repair rate $\Theta(x) = \Theta(y) = \Theta(z) = \Theta(k) = \omega_1(x) = \omega_1(y) = \omega_1(z) = \omega_1(k) = 0$ in equation (60) and taking limit, as x tend to zero we obtain the expression for MTTF as:

$$\text{MTTF} = \lim_{x \to 0} P_{up}(S).$$

Setting the values of failure rate as $\varphi_2 = 0.002, \varphi_3 = 0.003, \varphi_4 = 0.004$

and varying $\varphi_1$ one by one respectively as 0.0001, 0.0002, 0.0003, 0.0004, 0.0005, 0.0006, 0.0007, 0.0008, and 0.0009.

Subsequently, we vary $\varphi_2, \varphi_3$ and $\varphi_4$ respectively by fixing the values of others.

Table 4: MTTF as function of Failure rate

| Failure Rate | MTTF $\delta_1$ | MTTF $\delta_2$ | MTTF $\delta_3$ | MTTF $\delta_4$ |
|--------------|-----------------|-----------------|-----------------|-----------------|
| 0.001        | 1087.86         | 250.278         | 229.458         | 297.953         |
| 0.002        | 705.291         | 208.567         | 222.482         | 260.709         |
| 0.003        | 522.365         | 182.023         | 208.567         | 231.741         |
| 0.004        | 415.094         | 162.684         | 194.152         | 208.567         |
| 0.005        | 344.568         | 147.603         | 180.750         | 189.606         |
| 0.006        | 294.662         | 135.357         | 168.678         | 173.806         |
| 0.007        | 257.484         | 25.142          | 157.905         | 160.436         |
| 0.008        | 228.715         | 116.452         | 148.304         | 148.976         |
d. Sensitivity analysis corresponding to (MTTF)

The sensitivity in MTTF of the system can be studied through the partial differentiation of MTTF with respect to the failure rate of the system. By applying the set of parameters $\varphi_1 = 0.001, \varphi_2 = 0.002, \varphi_3 = 0.003, \varphi_4 = 0.004$, in the partial differentiation of MTTF, one can calculate the MTTF sensitivity as shown in the Table below and corresponding graphs shown in Figure…

Table 5. MTTF sensitivity as function of failure rate

| Failure Rate | $\frac{\partial (MTTF)}{\varphi_1}$ | $\frac{\partial (MTTF)}{\varphi_2}$ | $\frac{\partial (MTTF)}{\varphi_3}$ | $\frac{\partial (MTTF)}{\varphi_4}$ |
|--------------|------------------|------------------|------------------|------------------|
| 0.001        | -500000          | -55614.2         | 2567.81          | -42564.6         |
| 0.002        | -200000          | -31978.9         | -12374.4         | -32588.6         |
| 0.003        | -100000          | -22235.0         | -14606.6         | -25749.0         |
| 0.004        | -85098.5         | -16893.6         | -14013.8         | -20856.7         |
| 0.005        | -58449.6         | -13492.9         | -12747.6         | -17236.9         |
| 0.006        | -42611.4         | -11127.6         | -11405.3         | -14483.8         |
| 0.007        | -32437.5         | -9385.50         | -10162.8         | -12341.2         |
| 0.008        | -25516.3         | -8050.60         | -9063.84         | -10641.2         |
| 0.009        | -20595.5         | -6997.48         | -8108.04         | -9269.64         |
e. Cost analysis

The expression for the expected profit incurred in \([0, t]\)

\[
E_p(t) = K_t \int_0^t P_p(t)dt - K_2 t
\]

Taking fixed values of parameters of equation (56), the subsequent equation (62) follows;

\[
E_p(t) = \{-0.0000159e^{-1.003t} + 0.00371706e^{-2.728442t} + 0.00343665e^{-1.025044t} - 0.0005797e^{-1.0148018t} + 0.99656124e^{-0.000051053} - 0.00311935e^{-1.0060000t}\} - K_2 t
\]

Supposing \(K_1 = 1\) and \(K_2 = 0.1, 0.2..., 0.6\), respectively and varying \(t = 0, 1, 2...10\), units of time, the expected profit calculations are done in Table below.

| Time | \(E_p(t)\) | \(E_p(t)\) | \(E_p(t)\) | \(E_p(t)\) | \(E_p(t)\) | \(E_p(t)\) |
|------|-------------|-------------|-------------|-------------|-------------|-------------|
|      | \(K_2=0.1\)| \(K_2=0.2\)| \(K_2=0.3\)| \(K_2=0.4\)| \(K_2=0.5\)| \(K_2=0.6\)|
| 0    | 0           | 0           | 0           | 0           | 0           | 0           |
| 10   | 3.9710      | 4.9710      | 5.9711      | 6.9710      | 7.9710      | 8.9710      |
| 20   | 7.8882      | 9.8882      | 11.888      | 13.888      | 15.888      | 17.888      |
| 30   | 11.752      | 14.752      | 17.752      | 20.752      | 23.752      | 26.752      |
| 40   | 15.563      | 19.563      | 23.563      | 27.563      | 31.563      | 35.563      |
| 50   | 19.320      | 24.320      | 29.320      | 34.320      | 39.320      | 44.320      |
| 60   | 23.026      | 29.026      | 35.026      | 41.026      | 47.026      | 53.026      |
| 70   | 26.769      | 33.678      | 40.679      | 47.679      | 54.679      | 61.679      |
5. Interpretation of the Results and Conclusion

Table 2 and Figure 3 demonstrate how the availability and likelihood of failure of the complicated repairable device change over time when failure rates are set at different values. As failure rates are reduced to lower levels, such as $\varphi_1 = 0.0001$, $\varphi_2 = 0.0002$, $\varphi_3 = 0.0003$, and $\varphi_4 = 0.0004$, the availability of the system diminishes with time and eventually stabilizes at the value. As a result, the graphical representation of the model shows that one may reliably portray the future behavior of a complex system at any moment for any given set of parametric parameters. The addition of copula increases the system's dependability substantially, as seen in Table 3 and Figure 4. As the model's graphical depiction demonstrates, any collection of parametric values may be used to forecast the future behavior of a complex system at any moment. Figure 4 of the investigation focused on the system's reliability while a fix is unavailable. When the availability and reliability numbers in Tables 2 and 3 are compared, it is obvious that the device performs significantly better when fixed than when replaced. When all other parameters are maintained.
constant, Table 4 and Figure 5 give the system's mean-time-to-failure (MTTF) with respect to variation in failure rates, \( \varphi_1 \), \( \varphi_2 \), \( \varphi_3 \), and \( \varphi_4 \). Color graphs (blue, green, pink, and yellow) are used to display the information. The Gumbel-Hougaard family copula is also used to evaluate the system. The study found that including copula substantially enhances the system's reliability.

The paper's analytic section includes a sensitivity analysis of the system. The fluctuation in sensitivity with variation in parameter values is shown in Table 5 and Figure 6.

Fuzzy methods will be used in the future to analyze the reliability and performance of multi-unit solar systems for small and large-scale industrial usage.

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