Global and Stochastic Analysis
Vol. 11 No. 2 (March, 2024)

Received: 30th November 2023 *Revised: 25th January 2024* *Accepted: 29th January 2024*

A NOVEL STOCHASTIC FRAMEWORK FOR AVAILABILITY OPTIMIZATION OF HARVESTING SYSTEMS

ASHISH KUMAR, NAVEEN KUMAR, MONIKA SAINI*, AND DEEPAK SINWAR

Abstract. The prominent objective of present study is to develop an efficient stochastic framework for availability evaluation of harvesting system (HS) using the concept of partial failure of subsystems. A harvesting system is very complex structure configured with four subsystems in series structure. The failure and repair laws of all subsystems are exponentially distributed. The sufficient repair facility available with system and harvesting system work as new after repair. Markovian birth-death methodology is opted for development of Chapman-Kolmogorov differential-difference equations of proposed stochastic framework. The steady state availability of HS system is derived for a particular case. Later, an effort is made to predict the optimal availability and respective optimal parameters of subsystems using metaheuristics algorithms. It is revealed that HS can attain optimal limit of availability 0.9999967 at population size 5 after 25 iterations. This study adds to the body of knowledge about harvesting systems by providing an all-encompassing viewpoint on availability optimization. The study's findings can be utilized in designing reliable harvesting systems. The proposed methodology can be used in other similar kind of mechanical systems.

1. Introduction

Agriculture plays an important role in economic development of any nation. As well as it can also contributes to achieve the world's development goals by providing healthy, sustainable, and inclusive food systems. But due to climate change agriculture production affected. Several times ripened crops destroyed in lack proper and timely harvesting. So, a proper and efficient harvesting system is needed to avoid this economic loss to farmers and maintain the sustainable supply of food grains. In this scenario, harvesting system play a prominent role for timely harvesting the crop. It is a crucial and complex part of agriculture in which several subsystems viz. tractor, combine, wagon, and human work together to successfully gather crops. In the harvesting system human ensure the coordinated and fruitful harvest by operating the machinery, tractor ensures supply power, combine do the harvesting, and wagon facilitate crop transportation. Due to the involvement of various subsystems, harvesting system and other agricultural machinery become complex. Lub *et al.* [5] analysed the impact of technology systems in agricultural crop harvesting, with a special focus on sugar beets. Fue *et al.* [6] assessed the

---

2000 *Mathematics Subject Classification.* 90B25 and 60K10.
Key words and phrases. Harvesting system, Stochastic modeling, Availability optimization, Metaheuristic algorithms, Markovian approach.
* Corresponding author.

prospects and obstacles in the field of agricultural robotics, particularly in the context of cotton harvesting. Idoje *et al.* [7] studied the revolutionary influence of smart technology and the Internet of Things (IoT) in agriculture. It examined cutting-edge technology, their uses in the production of crops and animals, and the difficulties and knowledge gaps to improve the sustainability and global food supply. Xaliqulov *et al.* [8] presented a bibliometric database on root harvesters from 1982 to 2022. The complexity of the system causes several kinds of snags and faults that influences the functioning of the harvesting. In such conditions it becomes necessary to design and operate these machines with high reliability and availability. Several studies conducted to evaluate the reliability measures of process industries, mechanical equipment and industrial systems using several methodologies viz. Markovian approach, semi-Markovian approach, minimal cut set and tie set approach etc. Madalli [3] talked about the difficulties and solutions associated with harvesting metadata in fields related to agriculture. Dahiya *et al.* [4] analysed fuzzy reliability of a harvesting system. Saini *et al.* [2] developed a stochastic model and performed sensitivity analysis of condenser reliability. Colombo *et al.* [9] used Markovian models in reliability and availability analysis of engineering systems. In order to increase system availability and profit, the impact of fault coverage factor, failure rates, and repair rates observed on these measures. Though all these approaches provide the local solutions for the reliability measures and unable to predict the optimal reliability of system. For this purpose, several researchers used computational intelligence techniques and metaheuristic algorithms for estimation of parameters and reliability measures of these systems. Semaan *et al.* [1] evaluated the importance of cost as an optimization parameter in the size of rainwater harvesting systems. Some well-known optimization algorithms for reliability prediction are grey wolf optimization (GWO), particle swarm optimization (PSO), dragonfly algorithm (DA), grasshopper optimisation algorithm (GOA), moth flame optimizer (MFO), and sine cosine algorithm (SCA). Maroufpoor *et al.* [10] used GWO and adaptive neural fuzzy inference system as a hybrid model for soil moisture simulation. It is evident from the facts and figures discussed above that the harvesting system's availability optimization has not contemplated yet. It motivates to develop an efficient stochastic model for harvesting system. The main contribution of present study is summarized as follows:

- Development of stochastic framework for steady-state availability evaluation of harvesting system.
- Availability optimization of proposed framework of harvesting system using metaheuristic algorithms GWO, PSO, DA, GOA, MFO and SCA.
- Investigation of impact of increased failure and repair rates on availability of harvesting system.

By keeping above facts in mind, here an efficient stochastic framework for availability evaluation of harvesting system (HS) is proposed under the concept of exponentially distributed failure and repair laws. The sufficient repair facility available with system and harvesting system work as new after repair. Markovian birth-death methodology is opted for development of Chapman-Kolmogorov differential-difference equations of proposed stochastic framework. The steady state availability of HS system is derived for a particular case. Later, an effort is made to predict the optimal availability and respective optimal parameters of subsystems using metaheuristics algorithms. The study's findings can be utilized in designing reliable harvesting systems. The proposed methodology can be used in other similar kind of mechanical systems.

2. Material and Methods

2.1. Notations. A stochastic model of complex harvesting system is developed using notations appended in Table 1.

TABLE 1. Taxonomy for Stochastic model development

S. No.	Sub-system	Mode				Failure rate/hr.α_i		Repair rate/hr.μ_i	
		Working Mode		Failure Mode					
1	Human	A		a		α_1		μ_1	
2	Tractor	B	B'	B'	b	α_2	α_5	μ_2	μ_2
3	Combine	C	C'	C'	c	α_3	α_6	μ_3	μ_3
4	Wagon	D	$D1$	$D1$	d	α_4	α_7	μ_4	μ_4

$P_1'(t)$: Represent derivative of the $P_1(t)$
$P_1(t)$: At time t, the system is in the initial state
$\circ$: Operational state $\square$: State of failure

2.2. Harvesting System Description. This section explains the operational procedure of the complex harvesting system and its configuration. The proposed system is made up of four subsystems: human, tractor, combine and wagon.

2.2.1. *Human.* For harvesting systems successful operation, involvement of human is essential. A harvesting operation's efficiency, sustainability, and ability to perform its assigned task are all guaranteed by effective human engagement. The suggested system human is considered as a single unit subsystem whose failure and repair rates are exponentially distributed and its failure causes complete system failure.

2.2.2. *Tractor.* The mainstay of contemporary harvesting methods is tractor. They offer the strength, agility, and adaptability required to carry out a variety of jobs in forestry and agriculture operations. They are a crucial part of mechanical harvesting procedures since they not only improve efficiency but also lessen the physical demands on human work. Consists of a single unit, and when it failed, the entire system failed. With an exponential distribution of the failure and repair rates, it might continue to function in a partially failed condition.

2.2.3. *Combine.* Because they combine numerous key duties into a single equipment, combines are the workhorses of grain crop harvesting systems. Their efficiency, precision, and versatility make them important in modern agriculture, letting farmers to rapidly and efficiently harvest, thresh, separate, and clean grain harvests. Consists of a single unit, and its failure caused the entire system to fail, with failure and repair rates exponentially distributed. It may remain operational in a partially failed state with an exponentially distributed failure and repair rate.

2.2.4. *Wagon.* Wagons serve an important part in harvesting systems by moving harvested crops from the field to storage or processing areas, facilitating harvest collecting and logistics. It is made up of a single unit, and its failure caused the entire system to fail. A backup unit ($D1$) is available. Its failure and repair rates follow an exponential distribution.

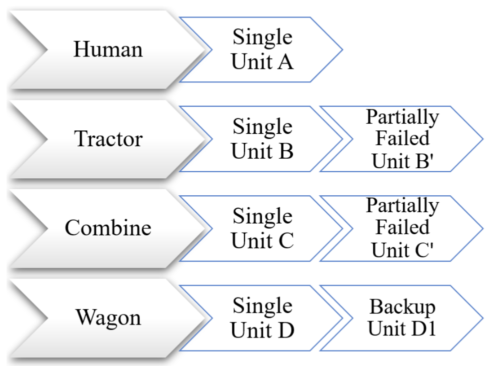

FIGURE 1. Flow chart of harvesting system

TABLE 2. Failure and repair rates of subsystems

Subsystems	Availability and Markov Analysis Base values		Search space of metaheuristics algorithms	
	Failure Rates	Repair rates	Failure Rates	Repair rates
Human	$\alpha_1 = 0.0011$	$\mu_1 = 0.083$	[0.000009-0.0871]	[0.000079-2.757]
Tractor	$\alpha_2 = 0.0017$	$\mu_2 = 0.091$	[0.000019- 0.0448]	[0.000089-2.349]
	$\alpha_5 = 0.0057$	$\mu_2 = 0.091$	[0.000049- 0.0886]	[0.000089-2.349]
Combine	$\alpha_3 = 0.0021$	$\mu_3 = 0.052$	[0.000029-0.0915]	[0.000099-3.315]
	$\alpha_6 = 0.0048$	$\mu_3 = 0.052$	[0.000059-0.0784]	[0.000099-3.315]
Wagon	$\alpha_4 = 0.0041$	$\mu_4 = 0.046$	[0.000039-0.0939]	[0.000099-1.356]
	$\alpha_7 = 0.0061$	$\mu_4 = 0.046$	[0.000069-0.0989]	[0.000099-1.356]

2.3. Optimization Strategies. The reliability evaluation techniques like semi-Markovian Approach, Markov approach, minima cut set etc. provide the local solution to the reliability evaluation problems. In order to predict the optimal availability of the systems, the utilization of modern computational intelligence techniques is solicited. In this regard, metaheuristic approaches are found to be suitable for solving such problems. Due to the nature of the objective function and constraints GWO (Grey Wolf Optimizer), PSO (Particle Swarm Optimizer), DA (Dragonfly Algorithm), GOA (Grasshopper Optimisation Algorithm), MFO (Moth-Flame Optimization) and SCA (Sine Cosine Algorithm) are well recommended techniques for availability optimization of process industries. GWO proposed by Mirjalili *et al.* [11] is a method inspired by nature that is used to solve complex optimization issues. It uses grey wolves' social order and hunting behavior to iteratively improve solutions and discover optimal outcomes across multiple areas. PSO developed by Kennedy and Eberhart [12] is a population-based metaheuristic technique that models the behavior of birds or particles. It optimizes the problem by iteratively changing solution candidates in complex search spaces to obtain the best potential solution. PSO strikes a balance between exploration and exploitation in order to find optimal or near-optimal solutions. Dragonfly Algorithm as proposed by Mirjalili [13] is an also an optimization method that balances the exploration and exploitation to find optimal or nearly optimal solutions in a variety of domains by modeling the swarming behavior of dragonflies, which allows for fast exploration of complex solution spaces. Grasshopper Optimisation Algorithm as developed by Saremi *et al*. [14] is a metaheuristic method that mimics the swarming and foraging behaviour of grasshoppers, drawing inspiration from nature. It is a global optimization that solves complicated problems through iteratively improving candidate solutions and adjusting to changing environmental variables. Moth Flame Optimizer (Mirjalili [15]) is a metaheuristic algorithm that draws inspiration from the way moths navigate artificial lighting. MFO seeks to identify global or near-global optima in a variety of optimization areas by iteratively improving solutions to complex problems. Sine Cosine Algorithm (Mirjalili [13]) solve optimization challenges by iteratively improves potential solutions by simulating the oscillatory behavior of the sine and cosine functions. SCA effectively searches through intricate search spaces to find the best or almost best answers to a variety of optimization issues.

2.4. Experimental Setup. The investigation is performed on RStudio using Windows10 64-bit with 4 GB of primary RAM and an Intel Core i3 5th generation CPU.

3. Stochastic Modeling of Harvesting System

In this section, Chapman-Kolmogorov differential equations associated with the proposed stochastic framework of harvesting system is developed using Markovian birth-death process. The set of Chapman-Kolmogorov differential equations is given below:

$$[P_1(t+\delta t) = (1-(\alpha_1+\alpha_2+\alpha_3+\alpha_4)\delta t)P_1(t) + \mu_1 P_2(t)\delta t + \mu_2 P_3(t)\delta t + \mu_3 P_4(t)\delta t + \mu_4 P_5(t)\delta t$$

$$\Rightarrow \quad \frac{P_1(t+\delta t)-P_1(t)}{\delta t} = -(\alpha_1+\alpha_2+\alpha_3+\alpha_4)P_1(t) + \mu_1 P_2(t) + \mu_2 P_3(t) + \mu_3 P_4(t) + \mu_4 P_5(t)$$

Taking limit $\delta t \to 0$, we get

$$P_1'(z) = -(\alpha_1+\alpha_2+\alpha_3+\alpha_4)P_1(t) + \mu_1 P_2(t) + \mu_2 P_3(t) + \mu_3 P_4(t) + \mu_4 P_5(t) \tag{3.1}$$

Similarly,

$$P_2'(t) = -\mu_1 P_2(t) + \alpha_1 P_1(t), \tag{3.2}$$

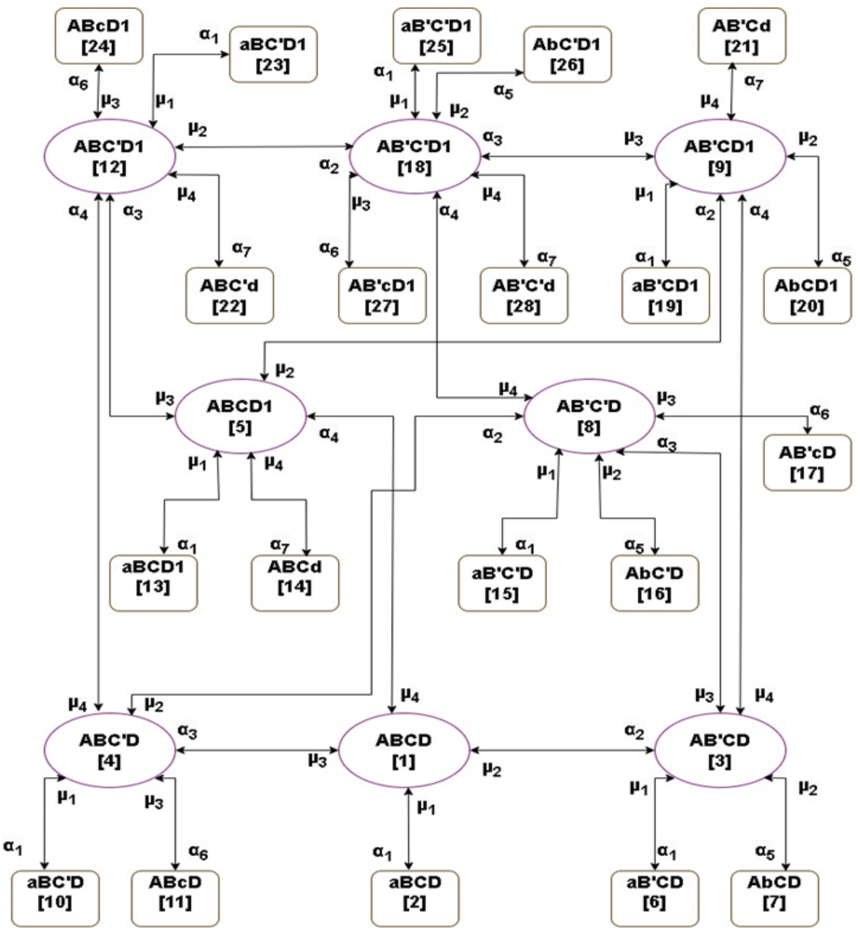

FIGURE 2. State transition diagram of harvesting system

$$P_3'(t) = -(\alpha_1 + \alpha_5 + \alpha_3 + \alpha_4 + \mu_2)P_3(t) + \mu_1 P_6(t) + \mu_2 P_7(t) + \mu_4 P_9(t) + \mu_3 P_8(t) + \alpha_2 P_1(t), \tag{3.3}$$

$$P_4'(t) = -(\alpha_1 + \alpha_2 + \alpha_6 + \alpha_4 + \mu_3)P_4(t) + \mu_1 P_{10}(t) + \mu_2 P_8(t) + \mu_3 P_1(t) + \mu_3 P_{11}(t) + \mu_4 P_{12}(t), \tag{3.4}$$

$$P_5'(t) = -(\alpha_1 + \alpha_7 + \alpha_2 + \alpha_3 + \mu_4)P_5(t) + \mu_1 P_{13}(t) + \mu_4 P_{14}(t) + \alpha_4 P_1(t) + \mu_2 P_9(t) + \mu_3 P_{12}(t), \tag{3.5}$$

$$P_6'(t) = -\mu_1 P_6(t) + \alpha_1 P_3(t), \tag{3.6}$$

$$P_7'(t) = -\mu_2 P_7(t) + \alpha_5 P_3(t), \tag{3.7}$$

$$P_8'(t) = -(\alpha_1 + \mu_2 + \alpha_4 + \alpha_6 + \alpha_5 + \mu_3)P_8(t) + \mu_1 P_{15}(t) + \alpha_2 P_4(t) + \mu_4 P_{18}(t) + \mu_3 P_{17}(t) + \alpha_3 P_3(t) + \mu_2 P_{16}(t), \tag{3.8}$$

$$P'_9(t) = -(\alpha_1 + \alpha_3 + \mu_2 + \alpha_7 + \mu_4 + \alpha_5)P_9(t) + \mu_1 P_{19}(t) + \mu_3 P_{18}(t) + \mu_4 P_{21}(t) + \mu_2 P_{20}(t) + \alpha_4 P_3(t) + \alpha_2 P_5(t), \tag{3.9}$$

$$P'_{10}(t) = -\mu_1 P_{10}(t) + \alpha_1 P_4(t), \tag{3.10}$$

$$P'_{11}(t) = -\mu_3 P_{11}(t) + \alpha_6 P_4(t), \tag{3.11}$$

$$P'_{12}(t) = -(\alpha_1 + \alpha_2 + \alpha_7 + \mu_3 + \mu_4 + \alpha_6)P_{12}(t) + \mu_1 P_{23}(t) + \mu_2 P_{18}(t) + \mu_4 P_{22}(t) + \alpha_3 P_5(t) + \alpha_4 P_4(t) + \mu_3 P_{24}(t), \tag{3.12}$$

$$P'_{13}(t) = -\mu_1 P_{13}(t) + \alpha_1 P_5(t), \tag{3.13}$$

$$P'_{14}(t) = -\mu_4 P_{14}(t) + \alpha_7 P_5(t), \tag{3.14}$$

$$P'_{15}(t) = -\mu_1 P_{15}(t) + \alpha_1 P_8(t), \tag{3.15}$$

$$P'_{16}(t) = -\mu_2 P_{16}(t) + \alpha_5 P_8(t), \tag{3.16}$$

$$P'_{17}(t) = -\mu_3 P_{17}(t) + \alpha_6 P_8(t), \tag{3.17}$$

$$P'_{18}(t) = -(\alpha_1 + \alpha_5 + \mu_3 + \alpha_7 + \mu_4 + \alpha_6 + \mu_2)P_{18}(t) + \mu_1 P_{25}(t) + \mu_2 P_{26}(t) + \alpha_3 P_9(t) + \mu_4 P_{28}(t) + \alpha_4 P_8(t) + \mu_3 P_{27}(t) + \alpha_2 P_{12}(t), \tag{3.18}$$

$$P'_{19}(t) = -\mu_1 P_{19}(t) + \alpha_1 P_9(t), \tag{3.19}$$

$$P'_{20}(t) = -\mu_2 P_{20}(t) + \alpha_5 P_9(t), \tag{3.20}$$

$$P'_{21}(t) = -\mu_4 P_{21}(t) + \alpha_7 P_9(t), \tag{3.21}$$

$$P'_{22}(t) = -\mu_4 P_{22}(t) + \alpha_7 P_{12}(t), \tag{3.22}$$

$$P'_{23}(t) = -\mu_1 P_{23}(t) + \alpha_1 P_{12}(t), \tag{3.23}$$

$$P'_{24}(t) = -\mu_3 P_{24}(t) + \alpha_6 P_{12}(t), \tag{3.24}$$

$$P'_{25}(t) = -\mu_1 P_{25}(t) + \alpha_1 P_{18}(t), \tag{3.25}$$

$$P'_{26}(t) = -\mu_2 P_{26}(t) + \alpha_2 P_{18}(t), \tag{3.26}$$

$$P'_{27}(t) = -\mu_3 P_{27}(t) + \alpha_6 P_{18}(t), \tag{3.27}$$

$$P'_{28}(t) = -\mu_4 P_{28}(t) + \alpha_7 P_{18}(t) \tag{3.28}$$

The associated initial conditions are given as:

$$P_i(t=0) = \begin{cases} 1, & \text{if } i = 0, \\ 0, & \text{if } i \neq 0 \end{cases} \tag{3.29}$$

Applying limit $t \to \infty$ on above equations (1)-(28), the system converts into a system of linear equation along with initil condition (3.29). As sum of transition probabilities is one, i.e., $\sum_{i=1}^{28} P_i = 1$, we have

$$P_2 = \left(\frac{\alpha_1}{\mu_1}\right) P_1;\ P_3 = \left(\frac{\alpha_2}{\mu_2}\right) P_1;\ P_4 = \left(\frac{\alpha_3}{\mu_3}\right) P_1;\ P_5 = \left(\frac{\alpha_4}{\mu_4}\right) P_1;$$

$$P_6 = \left(\frac{\alpha_1}{\mu_1}\frac{\alpha_2}{\mu_2}\right) P_1;\ P_7 = \left(\frac{\alpha_5}{\mu_2}\frac{\alpha_2}{\mu_2}\right) P_1;\ P_8 = \left(\frac{\alpha_3}{\mu_3}\frac{\alpha_2}{\mu_2}\right) P_1;$$

$$P_9 = \left(\frac{\alpha_4}{\mu_4}\frac{\alpha_2}{\mu_2}\right) P_1;\ P_{10} = \left(\frac{\alpha_1}{\mu_1}\frac{\alpha_3}{\mu_3}\right) P_1;\ P_{11} = \left(\frac{\alpha_3}{\mu_3}\frac{\alpha_6}{\mu_3}\right) P_1;\ P_{12} = \left(\frac{\alpha_3}{\mu_3}\frac{\alpha_4}{\mu_4}\right) P_1;$$

$$P_{13} = \left(\frac{\alpha_1}{\mu_1}\frac{\alpha_4}{\mu_4}\right)P_1;\ P_{14} = \left(\frac{\alpha_4}{\mu_4}\frac{\alpha_7}{\mu_4}\right)P_1;\ P_{15} = \left(\frac{\alpha_1}{\mu_1}\frac{\alpha_2}{\mu_2}\frac{\alpha_3}{\mu_3}\right)P_1;;$$
$$P_{16} = \left(\frac{\alpha_5}{\mu_2}\frac{\alpha_2}{\mu_2}\frac{\alpha_3}{\mu_3}\right)P_1\ P_{17} = \left(\frac{\alpha_6}{\mu_3}\frac{\alpha_2}{\mu_2}\frac{\alpha_3}{\mu_3}\right)P_1;\ P_{18} = \left(\frac{\alpha_4}{\mu_4}\frac{\alpha_2}{\mu_2}\frac{\alpha_3}{\mu_3}\right)P_1;$$
$$P_{19} = \left(\frac{\alpha_1}{\mu_1}\frac{\alpha_2}{\mu_2}\frac{\alpha_4}{\mu_4}\right)P_1;\ ;P_{20} = \left(\frac{\alpha_2}{\mu_2}\frac{\alpha_4}{\mu_4}\frac{\alpha_5}{\mu_2}\right)P_1;\ P_{21} = \left(\frac{\alpha_2}{\mu_2}\frac{\alpha_4}{\mu_4}\frac{\alpha_7}{\mu_4}\right)P_1;$$
$$P_{22} = \left(\frac{\alpha_3}{\mu_3}\frac{\alpha_4}{\mu_4}\frac{\alpha_7}{\mu_4}\right)P_1;\ P_{23} = \left(\frac{\alpha_1}{\mu_1}\frac{\alpha_4}{\mu_4}\frac{\alpha_3}{\mu_3}\right)P_1;\ P_{24} = \left(\frac{\alpha_6}{\mu_3}\frac{\alpha_4}{\mu_4}\frac{\alpha_3}{\mu_3}\right)P_1;$$
$$P_{25} = \left(\frac{\alpha_1}{\mu_1}\frac{\alpha_2}{\mu_2}\frac{\alpha_4}{\mu_4}\frac{\alpha_3}{\mu_3}\right)P_1;\ P_{26} = \left(\frac{\alpha_5}{\mu_2}\frac{\alpha_2}{\mu_2}\frac{\alpha_4}{\mu_4}\frac{\alpha_3}{\mu_3}\right)P_1;\ P_{27} = \left(\frac{\alpha_6}{\mu_3}\frac{\alpha_2}{\mu_2}\frac{\alpha_4}{\mu_4}\frac{\alpha_3}{\mu_3}\right)P_1;$$
$$P_{28} = \left(\frac{\alpha_7}{\mu_4}\frac{\alpha_2}{\mu_2}\frac{\alpha_4}{\mu_4}\frac{\alpha_3}{\mu_3}\right)P_1, \tag{3.30}$$

where

$$\begin{aligned} P_1 = \Bigg[&1 + \left(\frac{\alpha_1}{\mu_1}\right) + \left(\frac{\alpha_2}{\mu_2}\right) + \left(\frac{\alpha_3}{\mu_3}\right) + \left(\frac{\alpha_4}{\mu_4}\right) \\ &+ \left(\frac{\alpha_2}{\mu_2}\right)\left\{\left(\frac{\alpha_1}{\mu_1}\right) + \left(\frac{\alpha_5}{\mu_2}\right) + \left(\frac{\alpha_3}{\mu_3}\right) + \left(\frac{\alpha_4}{\mu_4}\right)\right\} \\ &+ \left(\frac{\alpha_3}{\mu_3}\right)\left\{\left(\frac{\alpha_1}{\mu_1}\right) + \left(\frac{\alpha_6}{\mu_3}\right) + \left(\frac{\alpha_4}{\mu_4}\right)\right\} + \left(\frac{\alpha_4}{\mu_4}\right)\left\{\left(\frac{\alpha_1}{\mu_1}\right) + \left(\frac{\alpha_7}{\mu_4}\right)\right\} \\ &+ \left(\frac{\alpha_2\alpha_3}{\mu_2\mu_3}\right)\left\{\left(\frac{\alpha_1}{\mu_1}\right) + \left(\frac{\alpha_5}{\mu_2}\right) + \left(\frac{\alpha_6}{\mu_3}\right) + \left(\frac{\alpha_4}{\mu_4}\right)\right\} \\ &+ \left(\frac{\alpha_2\alpha_4}{\mu_2\mu_4}\right)\left\{\left(\frac{\alpha_1}{\mu_1}\right) + \left(\frac{\alpha_5}{\mu_2}\right) + \left(\frac{\alpha_7}{\mu_4}\right)\right\} \\ &+ \left(\frac{\alpha_4\alpha_3}{\mu_4\mu_3}\right)\left\{\left(\frac{\alpha_1}{\mu_1}\right) + \left(\frac{\alpha_6}{\mu_3}\right) + \left(\frac{\alpha_7}{\mu_4}\right)\right\} \\ &\cdot \left(\frac{\alpha_2\alpha_3\alpha_4}{\mu_2\mu_3\mu_4}\right)\left\{\left(\frac{\alpha_1}{\mu_1}\right) + \left(\frac{\alpha_5}{\mu_2}\right) + \left(\frac{\alpha_6}{\mu_3}\right) + \left(\frac{\alpha_7}{\mu_4}\right)\right\}\Bigg]^{-1} \end{aligned} \tag{3.31}$$

Using the above transition probabilities appended in equation (3.30), steady state availability (SSA) of harvesting system is derived as follows:

$$\begin{aligned} SSA &= P_1 + P_3 + P_4 + P_5 + P_8 + P_9 + P_{12} + P_{18} \\ &= \Bigg\{1 + \left(\frac{\alpha_2}{\mu_2}\right) + \left(\frac{\alpha_3}{\mu_3}\right) + \left(\frac{\alpha_4}{\mu_4}\right) + \left(\frac{\alpha_2\alpha_3}{\mu_2\mu_3}\right) + \left(\frac{\alpha_2\alpha_4}{\mu_2\mu_4}\right) \\ &\quad + \left(\frac{\alpha_4\alpha_3}{\mu_4\mu_3}\right) + \left(\frac{\alpha_2\alpha_3\alpha_4}{\mu_2\mu_3\mu_4}\right)\Bigg\}\Bigg[1 + \left(\frac{\alpha_1}{\mu_1}\right) + \left(\frac{\alpha_2}{\mu_2}\right) + \left(\frac{\alpha_3}{\mu_3}\right) + \left(\frac{\alpha_4}{\mu_4}\right) \\ &\quad + \left(\frac{\alpha_2}{\mu_2}\right)\left\{\left(\frac{\alpha_1}{\mu_1}\right) + \left(\frac{\alpha_5}{\mu_2}\right) + \left(\frac{\alpha_3}{\mu_3}\right) + \left(\frac{\alpha_4}{\mu_4}\right)\right\} \\ &\quad + \left(\frac{\alpha_3}{\mu_3}\right)\left\{\left(\frac{\alpha_1}{\mu_1}\right) + \left(\frac{\alpha_6}{\mu_3}\right) + \left(\frac{\alpha_4}{\mu_4}\right)\right\} + \left(\frac{\alpha_4}{\mu_4}\right)\left\{\left(\frac{\alpha_1}{\mu_1}\right) + \left(\frac{\alpha_7}{\mu_4}\right)\right\} \end{aligned}$$

$$+\left(\frac{\alpha_2\alpha_3}{\mu_2\mu_3}\right)\left\{\left(\frac{\alpha_1}{\mu_1}\right)+\left(\frac{\alpha_5}{\mu_2}\right)+\left(\frac{\alpha_6}{\mu_3}\right)+\left(\frac{\alpha_4}{\mu_4}\right)\right\}$$
$$+\left(\frac{\alpha_2\alpha_4}{\mu_2\mu_4}\right)\left\{\left(\frac{\alpha_1}{\mu_1}\right)+\left(\frac{\alpha_5}{\mu_2}\right)+\left(\frac{\alpha_7}{\mu_4}\right)\right\}$$
$$+\left(\frac{\alpha_4\alpha_3}{\mu_4\mu_3}\right)\left\{\left(\frac{\alpha_1}{\mu_1}\right)+\left(\frac{\alpha_6}{\mu_3}\right)+\left(\frac{\alpha_7}{\mu_4}\right)\right\}$$
$$\cdot\left(\frac{\alpha_2\alpha_3\alpha_4}{\mu_2\mu_3\mu_4}\right)\left\{\left(\frac{\alpha_1}{\mu_1}\right)+\left(\frac{\alpha_5}{\mu_2}\right)+\left(\frac{\alpha_6}{\mu_3}\right)+\left(\frac{\alpha_7}{\mu_4}\right)\right\}\Bigg]^{-1} \tag{3.32}$$

4. Numerical Results and Discussion

In this section, numerical results for availability of harvesting system derived for a particular case in two phases. Initially, the steady state availability of the proposed harvesting system is determined with respect to failure and repair rates. Later, the availability of the system is optimized by considering equation (3.32) as the objective function. It is also observed that how different failure and repair rates affect steady-state availability of harvesting system. The steady state availability of harvesting system appended in Table 3. It is revealed that the availability of the harvesting system declines sharply with the increase of failure rate (α_1) of subsystem human. Similarly, the failure rates of all subsystems increased 15%, and the effect on steady state availability is observed. It is identified that failure rate (α_4) of subsystem wagon influences the availability of the harvesting system sharply. The steady state availability decline from 0.9705784 to 0.8971419 with respect to failure rate (α_1) after 15% increase in the failure rate of wagon.

TABLE 3. Steady state availability behaviour of harvesting system with respect to various failure rates

α_1	Base Values	α_2 + 15% of α_2	α_3 + 15% of α_3	α_4 + 15% of α_4	α_5 + 15% of α_5	α_6 + 15% of α_6	α_7 + 15% of α_7
0.0011	0.9719712	0.9718119	0.9714863	0.9705784	0.9718085	0.9714638	0.9704358
0.0021	0.9607207	0.9605651	0.9602469	0.9593599	0.9605617	0.9602249	0.9592206
0.0031	0.9497277	0.9495756	0.9492646	0.9483978	0.9495723	0.9492431	0.9482617
0.0041	0.9389834	0.9388347	0.9385307	0.9376834	0.9388315	0.9385097	0.9375503
0.0051	0.9284794	0.9283340	0.9280369	0.9272083	0.9283309	0.9280163	0.9270782
0.0061	0.9182079	0.9180657	0.9177751	0.9169647	0.9180626	0.9177550	0.9168375
0.0071	0.9081611	0.9080220	0.9077377	0.9069450	0.9080191	0.9077181	0.9068206
0.0081	0.8983319	0.8981958	0.8979176	0.8971419	0.8981928	0.8978983	0.8970201

Numerical results for steady state availability of harvesting system with respect to variation repair rates is shown in Table 4. It is revealed that, the 15% variation in various repair rates μ_2, μ_3, and μ_4 resulted 0.027%, 0.084% and 0.251% variation occurs in the steady state availability of harvesting system. The highest gain in availability is observed corresponding to the wagon's repair rate (μ_4).

Table 4. Steady state availability behaviour of harvesting system with respect to various repair rates

μ_1	Base values	μ_2 + 15% of μ_2	μ_3 + 15% of μ_3	μ_4 + 15% of μ_4
0.183	0.978861548	0.979128023	0.979686246	0.981318548
0.283	0.980900944	0.981168531	0.981729083	0.983368206
0.383	0.981878385	0.982146505	0.982708176	0.984350572
0.483	0.982451994	0.982720427	0.983282755	0.984927074
0.583	0.982829189	0.983097829	0.983660588	0.985306173
0.683	0.983096107	0.983364893	0.983927958	0.985574438
0.783	0.983294940	0.983563835	0.984127128	0.985774275
0.883	0.983448793	0.983717772	0.984281242	0.985928905

Further in phase two, various metaheuristic algorithms viz. GWO, PSO, DA, GOA, MFO, and SCA applied on equation (3.32) to predict the optimal value of the harvesting system availability. The optimal solution is explored in the search space appended in Table 2. The various algorithm characteristics given in Table 5.

Table 5. Search space for metaheuristic algorithms

Algorithms	Parameters
Gray Wolf Optimization	Population size 5, 15, 25, 55, 155, 255, 555; Number of maximum iterations =2155
Particle Swarm Optimization	Population size 5, 15, 25, 55, 155, 255, 555; Number of maximum iterations = 2155; Maximum particle's velocity = 2; Inertia weight = 0.99; Individual cognitive = 1.5; Group cognitive = 2.8
Grasshopper Optimization Algorithm	Population size 5, 15, 25, 55, 155, 255, 555; Number of maximum iterations = 2155
Dragonfly Algorithm	Population size 5, 15, 25, 55, 155, 255, 555; Number of maximum iterations = 2155
Moth Flame Optimizer	Population size 5, 15, 25, 55, 155, 255, 555; Number of maximum iterations = 2155
Sine Cosine Algorithm	Population size 5, 15, 25, 55, 155, 255, 555; Number of maximum iterations = 2155

Tables 6-7 appended the predicted availability of harvesting system derived using various algorithms at various population sizes up to 2155 iteration size. It is observed that after 25 iterations, dragonfly algorithm predicts the highest availability of 0.9999961 at population size 255. Though all the other algorithm attains the optimum value 0.9999967 at the population size 5 after 25 iterations.

TABLE 6. Predicted availability of harvesting system at various population size

Algorithms	Population\ Iteration	25	55	105	155	555	1055	2155
GWO	5	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	15	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	25	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	55	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	155	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	255	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	555	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
PSO	5	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	15	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	25	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	55	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	155	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	255	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	555	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
DA	5	0.999993	0.9999954	0.9999931	0.999708	0.9970455	0.9999924	0.9994391
	15	0.9999899	0.9999921	0.999996	0.9997159	0.999992	0.9999962	0.9998805
	25	0.9999939	0.999993	0.9992904	0.9999963	0.9999967	0.9998729	0.9999803
	55	0.9968549	0.9999933	0.9999928	0.995068	0.9995924	0.9999954	0.9991013
	155	0.998734	0.9999963	0.9999957	0.9999925	0.9999941	0.9998868	0.999714
	255	0.9999961	0.9999954	0.9998378	0.9999829	0.9999941	0.9999327	0.9999934
	555	0.9999945	0.9999964	0.9995389	0.9999958	0.9998739	0.9999932	0.9999949

TABLE 7. Predicted availability of harvesting system at various population size

Algorithms	Population\ Iteration	25	55	105	155	555	1055	2155
GOA	5	0.9999967	0.9999963	0.9999965	0.9999967	0.9999967	0.9999964	0.9999967
	15	0.9999966	0.9999967	0.9999967	0.9999965	0.9999967	0.9999964	0.9999966
	25	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999964
	55	0.9999952	0.9999967	0.9999943	0.9999965	0.9999967	0.9999967	0.999995
	155	0.9999967	0.9999967	0.9999967	0.9999967	0.9999965	0.9999965	0.9999964
	255	0.9999967	0.9999967	0.9999965	0.9999967	0.9999967	0.9999966	0.9999967
	555	0.9999967	0.9999966	0.9999966	0.9999967	0.9999967	0.9999967	0.9999942
MFO	5	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	15	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	25	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	55	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	155	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	255	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	555	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
SCA	5	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	15	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	25	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	55	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	155	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	255	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967
	555	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967	0.9999967

5. Conclusion

For a particular case, steady state availability of the proposed stochastic model of harvesting system under concept of partial failure is derived with respect to failure and repair rates. The impact of variation in failure and repair rates is observed on steady state availability of harvesting system. It is observed that steady state availability increases with the increase of repair rates while sharply declined with the increment in failure rates. At 15% variation in repair rates μ_2, μ_3, and μ_4 availability shows 0.027%, 0.084% and 0.251% changes respectively. The availability of wagon is most sensitive. The maximum predicted availability by dragonfly algorithm is 0.9999961 at population size 255 after 25 iterations while other algorithms predict the optimal availability is 0.9999967 at population size 5 after 25 iterations. So, it is revealed that GWO, PSO, GOA, MFO and SCA outperform over dragonfly algorithm in prediction of availability of harvesting systems. The derived results can be used in designing the harvesting systems as well as planning the maintenance strategies for better operation of such equipment's. The proposed methodology can be used in performance evaluation of other similar kind of systems. The study is performed under the assumption of constant failure and repair rates further it may be carried out by considering arbitrarily distributed parameters.

Acknowledgment. Authors are thankful to the reviewers for giving suggestions to improve the quality of the work.

References

1. Semaan, M., Day, S.D., Garvin, M., Ramakrishnan, N., Pearce, A.: Optimal sizing of rainwater harvesting systems for domestic water usages: A systematic literature review, *Resources, Conservation and Recycling: X* **6** (2020) 100033.
2. Saini, M., Gupta, N., Kumar, A.: Stochastic modeling and sensitivity analysis of condenser in steam turbine power plants, *Global and Stochastic Analysis* **8**(2) (2021) 101–119.
3. Madalli, D.P.: Issues in harvesting resources from agricultural repositories, in *Research Conference on Metadata and Semantic Research*, pp. 414-422, Cham: Springer International Publishing (2013).
4. Dahiya, O., Kumar, A., Saini, M.: Performance evaluation and availability analysis of a harvesting system using fuzzy reliability approach, *Int. J. Recent Technol. Eng.* **7**(5) (2019) 248–254.
5. Lub, P., Pukas, V., Sharybura, A., Lysiuk, O.: Modelling of the technological systems projects of harvesting agricultural crops, in *2019 IEEE 14th International Conference on Computer Sciences and Information Technologies (CSIT)* **2**, pp. 19–22, (2019).
6. Fue, K.G., Porter, W.M., Barnes, E.M., Rains, G.C.: An extensive review of mobile agricultural robotics for field operations: focus on cotton harvesting, *Agri Engineering 2*(1) (2020).
7. Idoje, G., Dagiuklas, T. and Iqbal, M., 2021. Survey for smart farming technologies: Challenges and issues. *Computers & Electrical Engineering*, *92*, p.107104.
8. Xaliqulov, M., Kannazarova, Z., Norchayev, D., Juliev, M., Turkmenov, X., Shermuxamedov, X., Ibragimova, G., Abduraxmonova, S.: Root harvester machine: a review of papers from the Scopus database published in English for the period of 1982-2022, in *E3S Web of Conferences*, **402**, p. 10010, EDP Sciences (2023).
9. Colombo, D., Abreu, D.T., Martins, M.R.: Application of Markovian models in reliability and availability analysis: advanced topics, in *Safety and Reliability Modeling and its Applications*, pp. 91-160, Elsevier (2021).

10. Maroufpoor, S., Maroufpoor, E., Bozorg-Haddad, O., Shiri, J., Yaseen, Z.M.: Soil moisture simulation using hybrid artificial intelligent model: Hybridization of adaptive neuro fuzzy inference system with grey wolf optimizer algorithm, *Journal of Hydrology* **575** (2019) 544–556.
11. Mirjalili, S., Mirjalili, S.M., Lewis, A.: Grey wolf optimizer, *Advances in Engineering Software* **69** (2014) 46–61.
12. Kennedy, J., Eberhart, R.: Particle swarm optimization, in *IEEE Proceedings of ICNN'95 – International Conference on Neural Networks* **4** (1995) pp. 1942-1948.
13. Mirjalili, S.: Dragonfly algorithm: a new meta-heuristic optimization technique for solving single-objective, discrete, and multi-objective problems, *Neural Computing and Applications* **27** (2016) 1053–1073.
14. Saremi, S., Mirjalili, S., Lewis, A.: Grasshopper optimisation algorithm: theory and application, *Advances in Engineering Software* **105** (2017) 30–47.
15. Mirjalili, S.: Moth-flame optimization algorithm: A novel nature-inspired heuristic paradigm, *Knowledge-Based Systems* **89** (2015) 228–249.
16. Mirjalili, S.: SCA: a sine cosine algorithm for solving optimization problems, *Knowledge-Based Systems* **96** (2016) 120–133.

Ashish Kumar: Department of Mathematics & Statistics, Manipal University Jaipur, Jaipur 303007, India
Email address: ashishbarak2020@gmail.com

Naveen Kumar: Department of Mathematics & Statistics, Manipal University Jaipur, Jaipur 303007, India
Email address: ndeswal90@gmail.com

Monika Saini: Department of Mathematics & Statistics, Manipal University Jaipur, Jaipur 303007, India
Email address: drmnksaini4@gmail.com

Deepak Sinwar: Department of Computer and Communication Engineering, Manipal University Jaipur, Jaipur 303007, India
Email address: deepak.sinwar@gmail.com