JJMIE

Volume 4, Number 4, September 2010
ISSN 1995-6665
Pages 487 - 494

Jordan Journal of Mechanical and Industrial Engineering www.jjmie.hu.edu.jo

Mathematical Modeling and Performance Optimization for the Paper Making System of a Paper Plant

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Abstract

This paper deals with the mathematical modeling and performance optimization for the paper making system in a paper plant using Genetic Algorithm. The paper making system of a paper plant has four main subsystems, arranged in series and parallel. Considering exponential distribution for the probable failures and repairs, the mathematical formulation of the problem is done using probabilistic approach and differential equations are developed based on Markov birth-death process. These equations are then solved using normalizing conditions to determine the steady state availability of the paper making system. The performance of each subsystem of the paper making system in a paper plant has also been optimized using Genetic Algorithm. Therefore, the findings of the present paper will be highly useful to the plant management for the timely execution of proper maintenance decisions and hence to enhance the system performance.

Keywords: Performance Optimization, Paper Making System, Genetic Algorithm.

1. Introduction

The paper industry comprises of large complex engineering systems arranged in series, parallel or a combination of both the configurations. Some of these systems are chipping, cooking, washing, bleaching, screening, stock preparation and paper making. These systems are normally arranged in hybrid configuration. The important process of a paper industry, upon which the quality of paper depends, is the paper making process. In the process of paper formation, the chips from storage are fed in to a digester to form the pulp, which is processed through various subsystems called knotter, decker, opener and washing. Then the washed pulp is bleached to get chlorine free white pulp, which is further passed through screen and cleaner to separate out oversize and odd shape particles. After that, the stock of the pulp is prepared with the addtion of chemicals and fillers to change the paper properties and is stored in the tank. The pulp from the storage tank, with the help of pump, is fed to head stock of the paper making machine to adjust the thickness of the paper. The pulp runs over a wire mat running on rollers, and water from the pulp is sucked through vacuum pumps arranged in parallel. The wet paper passes through the heated rollers together with a synthetic belt (the press section) and is dried in drier section in two stages. The dried paper is finally rolled on a pope reel. The schematic flow diagram of paper making system is shown in figure1

1.1. Literature Review

The available literature reflects that several approaches have been used to analyze the steady state behavior of various systems. Dhillon et al. [1] have frequently used the Markovian approach for the availability analysis, using exponential distribution for failure and repair times. Kumar et al. [2, 3, and 4] dealt with reliability, availability and operational behavior analysis for different systems in the paper plant. Srinath [5] has explained a Markov model to determine the availability expression for a simple system consisting of only one component Gupta et al. [6] have evaluated the reliability parameters of butter manufacturing system in a diary plant considering exponentially distributed failure rates of various components. The reliability of the system is determined by forming the differential equations with the help of transition diagram using Markovian approach and then solving these differential equations with the help of fourth order Runge-Kutta method. They applied the recursive method for calculating long run availability and MTBF using numerical technique. Sunand et al. [7] dealt with maintenance management for ammonia synthesis system in fertilizer plant. Shooman [8] suggested different methods for the reliability computations of systems with dependent failures. Tewari et al. [9, 10] dealt with the determination of availability for the systems with elements

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exhibiting independent failures and repairs or the operation with standby elements for sugar industry. They also dealt with mathematical modeling and behavioral analysis for a refining system of a sugar industry using Genetic Algorithm. Sunand et al. [11] discussed simulated availability of CO_2 cooling system in a fertilizer plant. Rajiv et al. [12, 13] have developed decision support system for stock preparation system of paper plant. They also dealt with availability of bleaching system of paper plant. Kalyanmoy Deb [14] has explained the optimization techniques and how they can be used in the engineering problems. Goldberg [15] made a systematic study on G.A. mechanism, and identified three basic operators: reproduction, crossover and mutation. So that the G.A. has higher opportunity for obtaining near optimal solutions. Castro and Cavalca [16] presented an availability optimization problem of an engineering system assembled in series configuration which has the redundancy of units and teams of maintenance as optimization parameters. Genetic Algorithm was used to reach the objective of availability, considering installation and maintenance costs. Chales and Kondo [17] tackled a multi objective combinatorial optimization problem. They used Genetic Algorithm to optimize the availability and cost of a series and parallel repairable system. Ying-Shen Juang et al. [18] proposed a genetic algorithm based optimization model to optimize the availability for a series parallel system. The objective is to determine the most economical policy of component's mean time between failure (MTBF) and mean time to repair (MTTR).

2. System Description

The paper making system comprises of four main subsystems, which are as follows:

1. Subsystem G_1: This subsystem consists of a wire mat units in series used for depositing the suspended fiber on the top of wire mash (water from pulp is sucked by vacuum pumps).It also controls the width of paper sheet produced. Its failure causes complete failure of system.
2. Subsystem G_2: This subsystem consists of one synthetic belt units to supports the fiber running through press and dryer sections. Its failure causes complete failure of system.
3. Subsystem G_3: This subsystem consists of a number of rollers in series to help the wire mat and synthetic belt to roll on them smoothly. Failure of anyone of these will cause complete system failure.
4. Subsystem G_4: This subsystem consists of six vacuum pumps in parallel used for sucking water from pulp through wire mat. Four pumps remain operating at a time, while remaining two pumps are in standby. Complete failure of the system takes place only when more than two pumps fail at a time

This system is associated with a common steam supply and failure in this supply needs emergency attention. Failure in steam supply affects the subsystems (which are in good condition otherwise), resulting in further delay in operation of the system. λ_{32} and μ_{32} are the failure and repair rates for this special failure.

3. ASSUMPTIONS AND NOTATIONS

The transition diagram (figure-2) of paper making system shows the two states, the system can acquire i.e. full working and failed state. Based on the transition diagram, a performance-evaluating model has been developed. The following assumptions and notations are addressed in developing the probabilistic models for paper making system of the paper plant concerned:

Assumptions

1. Failure/repair rates are constant over time and statistically independent.
2. A repaired unit is as good as new, performance wise for a specified duration.
3. Sufficient repair facilities are provided, i.e. no waiting time to start the repairs.
4. Standby units (if any) are of the same nature and capacity as the active units.
5. System failure /repair follow exponential distribution.
6. Service includes repair and /or replacement.
7. System may work at a reduced capacity / efficiency.
8. There are no simultaneous failures among system. However, simultaneous failure may occur among various subsystems in a system.

Notations

The following notations are addressed for the purpose of mathematical analysis of the paper making system:

G_1, G_2, G_3, G_4 : Represent good working states of respective wire mat, synthetic belt, roller ,vacuum pump.

g_1, g_2, g_3, g_4 : Represent failed states of respective wire mat, synthetic belt, roller, vacuum pump.

$\lambda28,\lambda29,\lambda30,\lambda31$: Respective mean constant failure rates of G1, G2, G3, G4 .

$\mu_{28},\mu_{29},\mu_{30},\mu_{31}$: Respective mean constant repair rates of g1, g2, g3, g4.

λ_{32} : Failure rate of steam supply

μ_{32} : Repair rate of steam supply

P0(t) : State probability that the system is working at full capacity at time t.

$P_i(t)$: State probability that the system is in the i^{th} state at time t.

$P'_i(t)$: First-order derivative of the probabilities.

4. Mathematical Modeling

The mathematical modeling is carried out using simple probabilistic considerations and differential equations are developed on the basis of Markov birth-death process .These equations are further solved for determining the steady state availability of the paper making system. Various probability considerations give the following differential equations associated with the paper making system:

States 0, 4 & 8 - Full capacity working.

States 1 to 3, 5 to 7, 9 to 12 & 0SF to 12SF show that unit is in failed state due to complete failure of one or the other subsystem of the unit.

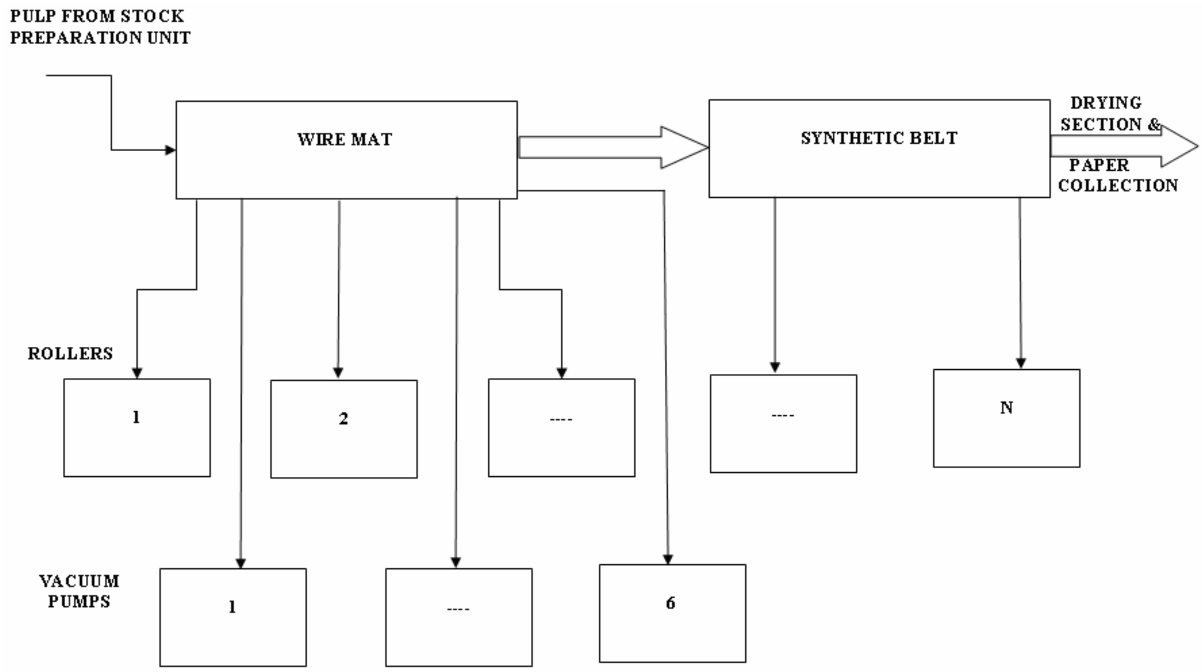

Figure 1. Schematic Flow Diagram of Paper Making System.

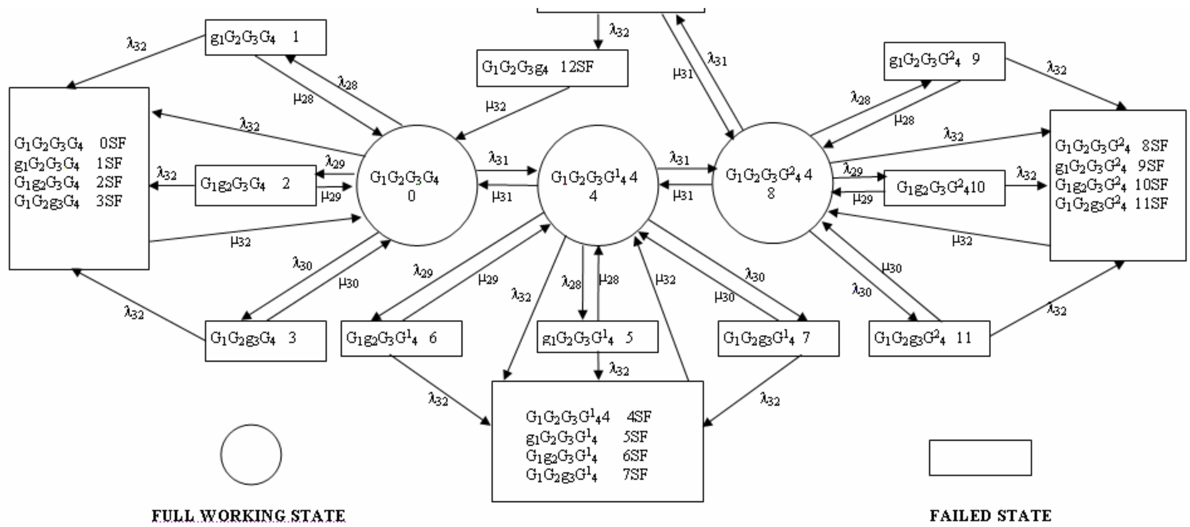

Figure 2. Transition Diagram of Paper Making System.

$$P'_0(t)+\sum_{i=28}^{32}\lambda_i P_0(t)=\sum_{i=28}^{31}\mu_i P_{i-27}(t)+\mu_{32}\sum_{j=0}^{3} P_{jSF}(t)+\mu_{32}P_{12SF}(t) \quad (1)$$

$$P'_4(t)+\sum_{i=28}^{32}\lambda_i P_4(t)+\mu_{31}P_4(t)=\sum_{i=28}^{31}\mu_i P_{i-23}(t)+\lambda_{31}P_0(t)+\mu_{32}\sum_{j=4}^{7} P_{jSF}(t) \quad (2)$$

$$P'_8(t)+\sum_{i=28}^{32}\lambda_i P_8(t)+\mu_{31}P_8(t)=\sum_{i=28}^{31}\mu_i P_{i-19}(t)+\lambda_{31}P_4(t)+\mu_{32}\sum_{j=8}^{11} P_{jSF}(t) \quad (3)$$

$$P'_i(t)+\lambda_{32}P_i(t)+\mu_{28}P_i(t)=\lambda_{28}P_j(t) \quad \text{where } i=1,5,9 \quad j=0,4,8 \quad (4)$$

$$P'_i(t)+\lambda_{32}P_i(t)+\mu_{29}P_i(t)=\lambda_{29}P_j(t) \quad \text{where } i=2,6,10 \quad j=0,4,8 \quad (5)$$

$$P'_i(t)+\lambda_{32}P_i(t)+\mu_{30}P_i(t)=\lambda_{30}P_j(t) \quad \text{where } i=3,7,11 \quad j=0,4,8 \quad (6)$$

$$P'_{iSF}(t)+\mu_{32}\sum_{i=0}^{12}P_{iSF}(t)=\sum_{i=0}^{12}\lambda_{32}P_j(t) \quad (7)$$

Where i=0,1,2,3,4,5,6,7,8,9,10,11,12 & j=0,1,2,3,4,5,6,7,8,9,10,11,12
With initial conditions at time t = 0
$P_i(t) = 1$ for i = 0= 0 for $i \neq 0$

5. Solution of Equations

5.1. Steady State Behavior

For steady state behavior, the various systems of a paper plant are expected to run failure free infinitely (for a very long period). So, the steady state availability (time independent performance behavior) of each unit/system may be obtained by setting d/dt =0 and $t \rightarrow \infty$ into respective equations i.e. (1) to (7) and then solving these equations recursively, we get:

$P_1=C_1P_0$ $P_2=C_2P_0$ $P_3=C_3P_0$ $P_4= LP_0$ $P_5= C_1LP_0$

$P_6= C_2LP_0$ $P_7= C_3LP_0$ $P_8= NLP_0$ $P_9= C_1NLP_0$ $P_{10}= C_2NLP_0$

$P_{11}= C_3NLP_0$ $P_{12}= MNLP_0$

$P_{0SF}=BP_0$ $P_{1SF}=BC_1P_0$ $P_{2SF}=BC_2P_0$ $P_{3SF}=BC_3P_0$

$P_{4SF}= BLP_0$ $P_{5SF}= B\,C_1LP_0$ $P_{6SF}= BC_2LP_0$ $P_{7SF}=BC_3LP_0$

P8SF= BNLP0 P9SF= BC1NLP0
P10SF= BC2NLP0 P11SF= BC3NLP0

P12SF= BMNLP0

Where

C1= λ28/(λ32+ μ28) C2= λ29/(λ32+ μ29) C2= λ29/(λ32+ μ29)

C3= λ30/(λ32+ μ30) L= λ31/{ λ31+ μ31-(N*μ31)} N= λ31/{ λ31+ μ31-(M*μ31)}

M= λ31/(λ32+ μ31) B= λ32/ μ32

Using Normalizing condition i.e. sum of all the state probabilities is equal to one

$$\sum_{i=0}^{12} P_i + \sum_{j=0}^{12} P_{jSF} = 1, \text{ we get:}$$

P0+C1P0 +C2P0 +C3P0+LP0+C1LP0+C2LP0+C3LP0 +NLP0 +C1NLP0 +C2NLP0+C3NLP0+MNLP0 +BP0+BC1P0+BC2P0+BC3P0+BLP0+BC1LP0+BC2LP0 +BC3LP0+BNLP0+BC1NLP0+BC2NLP0+ BC3NLP0 +BMNLP0 = 1

P0[(1+C1+C2+C3)+L(1+C1+C2+C3)+NL(1+C1+C2+C3 +M)+B(1+C1+C2+C3)+BL(1+C1+C2+C3)+BNL(1+C1+ C2+C3+M)]=1

P0(Z1+ LZ1+ NLZ2+ BZ1+ BLZ1+ BNLZ2)=1

P0[Z1 (1+ L+ B+ BL)+ Z2(NL+BNL)]=1

P0(Z1Y1+Z2Y2)=1

P0=1/(Z1Y1+Z2Y2) (8)

Where

Z1=1+C1+C2+C3

Z2=1+ C1+C2+C3+M

Y1= ((1+L+B+(B*L))

Y2=((N*L)+ (B*N*L))

Now, the steady state availability (Av.) of the paper making system is given by summation of all the full working and reduced capacity states probabilities.

Av.= P0+P4 +P8

Av.= P0+LP0 +NLP0

Av.= P0(1+L +NL)

Av.= [(1+L+(NL))/((Z1Y1)+(Z2Y2))] (9)

Here, system performance has been evaluated in terms of availability.

6. Genetic Algorithm

Genetic Algorithms are computerized search and optimization algorithms based on the mechanics of natural genetics and natural selection. Genetic Algorithms have become important because they are found to be potential search and optimization techniques for complex engineering optimization problems. The action of Genetic Algorithm is shown in figure-3 for parameter optimization in the present problem can be stated as follows:

1. Initialize the parameters of the Genetic Algorithm.
2. Randomly generate the initial population and prepare the coded strings.
3. Compute the fitness of each individual in the old population.
4. Form the mating pool from the old population.
5. Select two parents from the mating pool randomly.

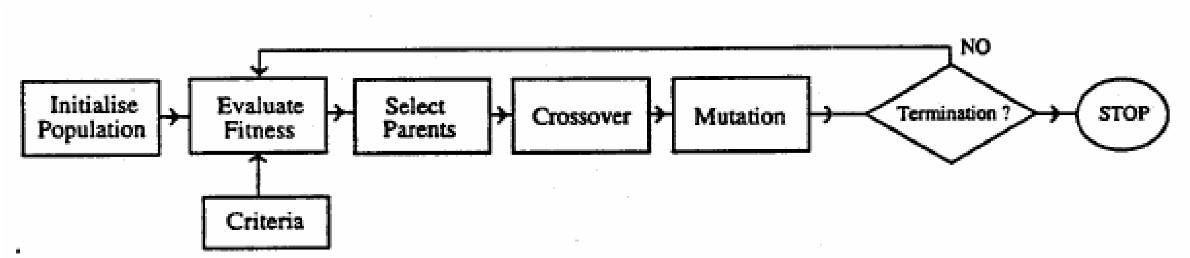

Figure 3

6. Perform the crossover of the parents to produce two off springs.
7. Mutate if required.
8. Place the child strings to new population.
9. Compute the fitness of each individual in new population.
10. Create best-fit population from the previous and new population.
11. Repeat the steps 4 to 10 until the best individuals in new population represent the optimum value of the performance function (System Availability).

7. Performance Optimization Using genetic Algorithm

The performance optimization of the paper making system is highly influenced by the failure and repair parameters of each subsystem. These parameters ensure high performance of the system. Genetic Algorithm is proposed to coordinate the failure and repair parameters of each subsystem for stable system performance i.e. high availability. Here, number of parameters is ten (five failure parameters and five repair parameters). The design procedure is described as follows:

To use Genetic Algorithm for solving the given problem, the chromosomes are to be coded in real structures. Unlike, unsigned fixed point integer coding parameters are mapped to a specified interval [X_{min} , X_{max}], where X_{min} and X_{max} are the minimum and maximum values of system parameters . The maximum value of the availability function corresponds to optimum values of system parameters. These parameters are optimized according to the performance index i.e. desired availability level. To test the proposed method, failure and repair rates are determined simultaneously for optimal value of unit availability. Effect of number of generations, population and crossover probability size on the availability of the paper making system is shown in Table 1, 2 and 3. To specify the computed simulation more precisely, trial sets are also chosen for Genetic Algorithm and system parameters. The performance [availability] of the paper making system is evaluated by using the designed values of the unit parameters.

Failure and Repair Rate Parameter Constraints are λ_{28}, μ_{28}, λ_{29}, μ_{29}, λ_{30}, μ_{30}, λ_{31}, μ_{31}, λ_{32}, μ_{32}

Parameters	λ_{28}	μ_{28}	λ_{29}	μ_{29}	λ_{30}	μ_{30}	λ_{31}	μ_{31}	λ_{32}	μ_{32}
Minimum	0.001	0.10	0.001	0.10	0.002	0.10	0.02	0.10	0.02	0.10
Maximum	0.005	0.50	0.005	0.50	0.006	0.50	0.10	0.50	0.10	0.50

Here, real-coded structures are used. The simulation is done to maximum number of generations, which is varying from 20 to 100**.** The effect of number of generations on availability of the paper making system is shown in figure4.

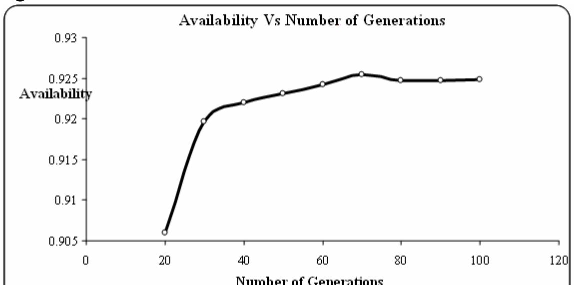

Figure: 4 Effect of Number of Generations on Fitness (Paper Making System Availability)

The optimum value of system's performance is **92.55%**, for which the best possible combination of failure and repair rates is **λ_{28} =0.0043, μ_{28} =0.3300, λ_{29} =0.0036, μ_{29} =0.3497, λ_{30} =0.0056, μ_{30} =0.2059, λ_{31} =0.0918, μ_{31} =0.1013, λ_{32} =0.0649, μ_{32} =0.1287at generation size 70** as given in table 1.

Now the simulation is done to maximum number of population size, which is varying from 20 to 100**.** The programme handled with the maximum value of the population size and terminated with heuristic result. The effect of population size on availability of the paper making system is shown in figure5.The optimum value of system's performance is **92.57%**, for which the best possible combination of failure and repair rates is **λ_{28} =0.0017, μ_{28} =0.4039, λ_{29} =0.0024, μ_{29} =0.1573, λ_{30} =0.0042, μ_{30} =0.2347, λ_{31} =0.0727, μ_{31} =0.1046, λ_{32} =0.0574, μ_{32} =0.1552at population size 70** as given in table 2.

Again, the simulation is done for maximum number of crossover probability, which is varying from 0.10 to 0.90. Crossover and mutation function performed through their selection with stochastic universal sampling. This function also performed through the double point crossover. The effect of crossover probability on availability of the paper making system is shown in figure 6.The optimum value of system's performance is **92.52%**, for which the best possible combination of failure and repair rates is **λ_{28} =0.0013, μ_{28} =0.3004, λ_{29} =0.004, μ_{29} =0.1436, λ_{30} =0.0035, μ_{30} =0.2291, λ_{31} =0.0815, μ_{31} =0.1051, λ_{32} =0.0996, μ_{32} =0.1298** at **crossover probability 0.60** as given in table 3.

Table 2: Effect of Population Size on Availability of the Paper Making System Using Genetic Algorithm.

Population Size	Availability	λ_{28}	μ_{28}	λ_{29}	μ_{29}	λ_{30}	μ_{30}	λ_{31}	μ_{31}	λ_{32}	μ_{32}
20	0.9048	.0044	.1	.0039	.1011	.0048	.3185	.0748	.1846	.0482	.1040
30	0.9181	.0034	.1304	.0039	.3018	.0042	.4039	.0973	.1195	.0426	.1639
40	0.9182	.0047	.1274	.0049	.1567	.0022	.2257	.1	.1	.0803	.3861
50	0.9247	.0045	.2707	.005	.2882	.0038	.4149	.0963	.1	.0958	.3917
60	0.9245	.0048	.1006	.005	.4704	.0042	.3867	.1	.1059	.0519	.3062
70	0.9257	.0017	.4039	.0024	.1573	.0042	.2347	.0727	.1046	.0574	.1552
80	0.9254	.0031	.1430	.0039	.1477	.0054	.3429	.0975	.1	.0251	.1134
90	0.9253	.005	.1585	.002	.1425	.006	.2308	.1	.1	.0564	.2492
100	0.9253	.0044	.1	.0042	.1492	.006	.2	.1	.1	.0986	.1021

(Mutation Probability=0.015, Number of Generations=80, Crossover Probability=0.85)

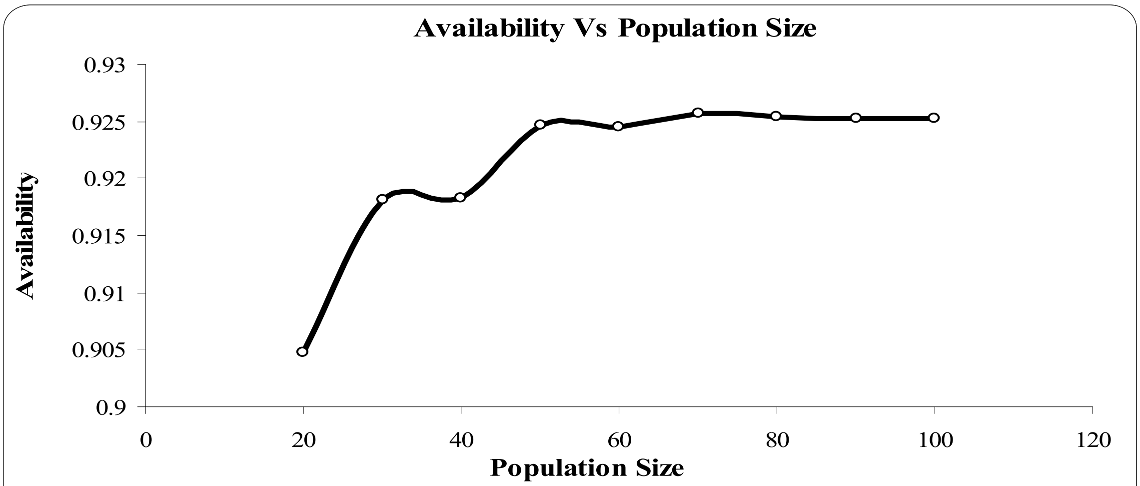

Figure: 5 Effect of Population Size on Fitness (Paper Making System Availability)

Table 3: Effect of Crossover Probability on Availability of the Paper Making System Using Genetic Algorithm.

Crossover Probability	Availability	λ_{28}	μ_{28}	λ_{29}	μ_{29}	λ_{30}	μ_{30}	λ_{31}	μ_{31}	λ_{32}	μ_{32}
.10	0.9191	.0048	.1691	.0035	.2076	.0048	.3171	.0985	.1028	.02	.2576
.20	0.9230	.0044	.2133	.0047	.1807	.0052	.3152	.0741	.1715	.0817	.1867
.30	0.9232	.0048	.3238	.0027	.2407	.0032	.2037	.0985	.1153	.0728	.1896
.40	0.9241	.005	.1539	.005	.1449	.006	.2046	.0967	.1017	.0232	.1259
.50	0.9241	.005	.1694	.0034	.4951	.0052	.3103	.0929	.1637	.0242	.4532
.60	**0.9252**	**.0013**	**.3004**	**.004**	**.1436**	**.0035**	**.2291**	**.0815**	**.1051**	**.0996**	**.1298**
.70	0.9251	.0039	.4425	.0046	.2063	.006	.4338	.0853	.2891	.0452	.2817
.80	0.9248	.0032	.3576	.0042	.1	.006	.2202	.1	.1002	.0931	.1294
.90	0.9247	.0023	.1056	.0024	.1663	.0049	.2696	.0968	.1074	.0912	.2012

(Mutation Probability=0.015, Number of Generations=80, Population Size=80)

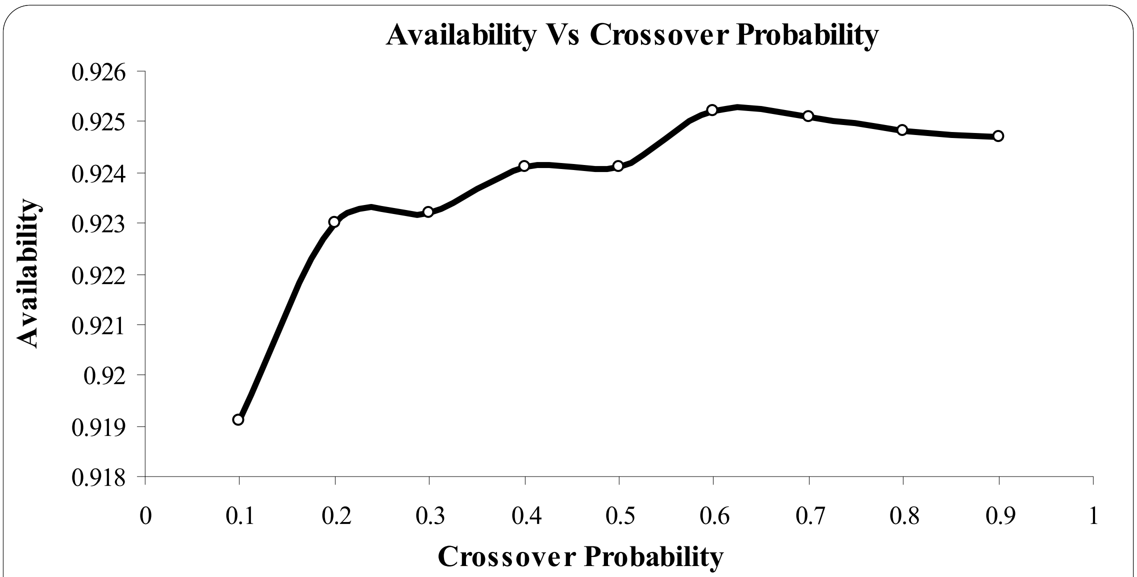

Figure:6 Effect of Crossover Probability on Fitness (Paper Making System Availability)

8. Conclusions

The mathematical modeling and performance optimization of the paper making system of a paper plant has been carried out in this paper. Genetic Algorithm Technique is hereby proposed to select the various feasible values of the system failure and repair parameters along with system availability levels. Finally, Genetic Algorithm Technique is successfully applied to coordinate simultaneously these parameters for determining an optimum level of system availability. Besides, the effect of Genetic Algorithm parameters such as number of generations, population size and crossover probability on the system performance i.e. availability has also been analyzed. By varying the above mentioned parameters of Genetic Algorithm the optimum system availability achieved is about 93% with best possible combinations of the failure and repair rates of all the subsystems of the paper making system. Then, the findings of this paper are discussed with the concerned paper plant management. Such results are found highly beneficial for the purpose of performance optimization of a paper making system in the paper plant concerned.

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