DECISION SUPPORT SYSTEM FOR UREA SYNTHESIS SYSTEM OF A FERTILIZER PLANT

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ABSTRACT

This paper introduces a decision support system for urea synthesis system of a fertilizer plant. It consists of five subsystems arranged in hybrid configurations. Decision support system for urea synthesis system has been designed with the help mathematical formulation using probabilistic approach. For this purpose, differential equations have been developed. Then steady state probabilities have determined. Besides, a pay off matrix is also developed which provides the various availability levels (Aii) for the different combinations of failure and repair rates for each subsystem. The optimum values of failure and repair rates for each subsystem are also determined. This decision model could be useful in a comparative evaluation of alternative maintenance strategies. So, the results of this paper would be highly useful in determining the optimal maintenance strategy, which will ensure the maximum availability of urea synthesis system in a fertilizer plant.

Key Words: Decision Support System, Decision Matrix, Availability.

1. INTRODUCTION

Fertilizer in India has emerged as one of the major import to meet the domestic demand. This gap between production and consumption is widening slowly because of lagging behind the production and increasing of the demand. Continuous efforts are needed to enhance production, which is based upon the development of efficient machines and maintenance strategies for full utilization of all the available resources (Kumar, Singh and Singh, J. 1988; Kumar and Pandey 1993). Production of fertilizer consists of three phases: developing phase (chemicals which are brought to the factory site), technological phase (balancing of equipment and input material, matching of man and machine) and research phase (modification of process parameters to obtain higher volume of fertilizers of specific qualities within the factory constraints (nature of the equipments used and concentration process).

There are physical limitations to develop the new chemicals, simultaneously, most of the Indian fertilizer plants are fairly well set i.e. their equipments are standardized and at a given capital investment, most of the companies are reluctant to add in the existing system unless they observe high benefit cost ratios (Sunand, Dinesh and Mehta 1996; Sunand, Dinesh and Mehta 1999).

A logical extension of the efforts to increase production in the fertilizer industry would be the maximization of fertilizer production at manufacturing stage (maximum utilization of maintenance crew and machine) keeping all other factors of the plant constant. In fertilizer industry a large number of equipments/ components are assembled to a basic skeleton to produce a final product, where the materials flow due to pressure difference from one section to another in some prearranged sequence. At each section a byproduct is separated due to change of pressure and / or temperature. Each section has a peculiar skeleton, each unit has a peculiar nature, and to achieve the goal of maximum production it is necessary to analysis the behavior of each unit of the section to economize operational parameters resulting in improved system availability. The analysis also helps in improving the process design and for reliable operation of the process (Dhillon and Singh 1981). A probabilistic analysis of the system under given operative conditions is helpful in the design modification for minimum failure of the units and to achieve the goal of optimum system availability. The units of the section are subjected to random failure and can be brought back into service by properly planned maintenance (Srinath 1994). Their operating behavior in the existing company environment is difficult to predict without knowing their interrelationship. Mathematical modeling is a tool to develop these relationships.

The fertilizer plant is a very large and complex engineering unit having continuous production of urea. It comprises of various systems viz. urea synthesis, urea decomposition, urea crystallization and urea prilling systems etc. For smooth running, each of its system should remain in upstate. One of the most important functionary systems is urea synthesis system, the subject of our discussion. In fertilizer plant the CO_2 gas and liquid ammonia NH_3 are fed to the urea synthesis reactor. The reactor is maintained at 190^0C temperature and 250 atm pressure and allows CO_2 and NH_3 to react forming urea in gaseous form. A repairable system is characterized by a large number of interconnected components with their own failure behavior and repair time distributions. System availability in such a case is a complex function of failure and repair time distributions of individual components within the system (Sunand, Dinesh and Mehta 2000, Sunand, Tewari and Rajiv 2007). The decision support system for the plant has been developed on the basis of an actual study conducted in a medium sized urea fertilizer plant situated near Delhi. The failure /repair time data in the plant were studied and based on the model behavioural analysis of the system is carried out. This paper discusses the decision support system of the urea synthesis system of a fertilizer plant.

2. THE UREA SYNTHESIS SYSTEM

The urea synthesis system comprises of a compressor used to compress the carbon dioxide, two reciprocating pumps used to boost the pressure of liquid ammonia and heaters, which are used to heat the ammonia gas. In this process the CO_2 gas and liquid ammonia NH_3 available from ammonia production process are fed to the urea synthesis reactor. In reactor these gases are react to forming urea in gaseous form (Kumar, Tewari and Sanjeev 2007).

2.1 System Description

The urea synthesis system consists of five subsystems arranged in series:

i) Subsystem (A1): CO_2 booster compressor is a single unit arranged in series. Its failure causes the complete failure of the system.

ii) Subsystem (A2): CO_2 compressor arranged in series, Failure of this subsystem causes the complete failure of the system.

iii) Subsystem (A3): Three NH_3 preheaters arranged in series. Failure of any one causes the complete failure of the system

iv) Subsystem (H): It consists of four liquid ammonia feed pumps arranged in parallel. Two pumps remain operative in parallel and other two in cold standby. Failure of three pumps at a time will cause complete failure of the system.

v) Subsystem (L): It comprises of three recycle solution feed pumps arranged in parallel. Failure of units reduces the capacity of the system but complete failure occurs when all units fail at a time.

2.2 Assumptions

The assumptions used in the performance modeling are (Dhillon and Singh 1981):

i) Failure/repair rates are constant over time and statistically independent.

ii) A repaired unit is as good as new one, far as performance is concerned.

(iii) Each subsystem has separate repair facility; there is no waiting time for repair in system.

(iv) The standby units/subsystems are of the same nature

(v) The system failure/repair follows exponential distribution.

(vi) The service includes repair and/or replacement of the units/subsystems.

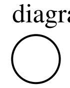
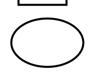
(vii) System may work at reduced capacity.

(viii) There are no simultaneous failures.

The transition diagram (Fig.1) of the urea synthesis system shows the various possible states, the system can acquire. Based on the transition diagram, a performance-evaluating model has been developed. The failures and repairs for this purpose have been modeled as birth and death process.

2.3 Nomenclature

The symbols and notations associated with transition diagram of the urea synthesis system.

	Indicates the system in operating condition.
	Indicates the system in breakdown condition
	Indicates the system in reduced capacity state.
Ai, H,L (i=1,2,3)	Indicate that the subsystems are working at full capacity.
Ai, h, λ	Indicates that all subsystems are in complete failed state.
H1,H2	Indicate that stand-by unit of the sub-system H is in operating state.
L1, L2	Indicate that the subsystem L is working at reduced capacity.
$P_0(t)$	Probability of the system working with full capacity at time 't'.
$P_1,(t),P_6(t)$	Probability of the system in cold standby state.
$P_2,(t) – P_5,(t)$,	Probability of the system in

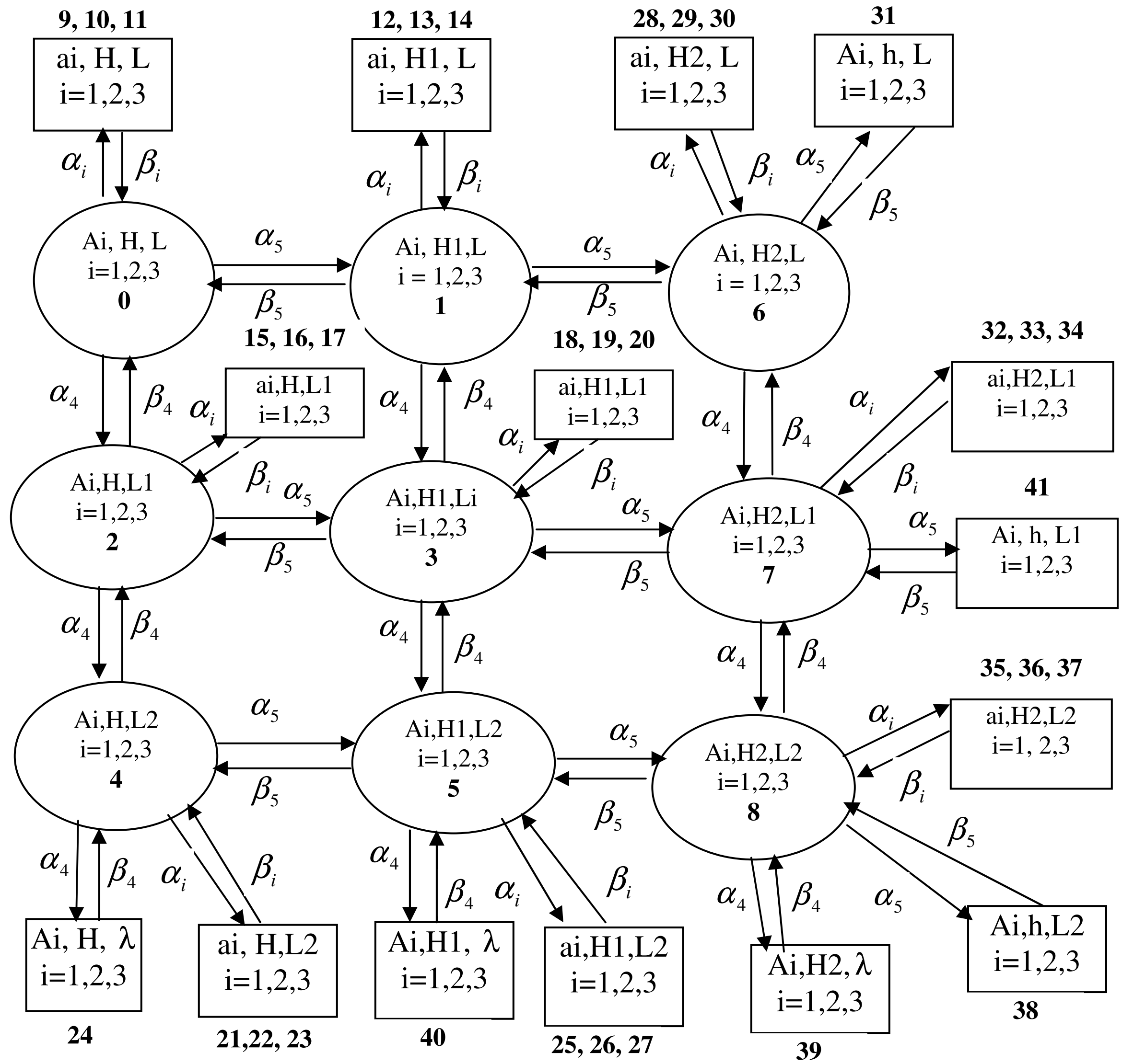


Figure 1: Transition Diagram of the Urea Synthesis System

$P_7(t), P_8(t)$	reduced capacity state.
$P_9(t)$ – $P_{41}(t)$	Probability of the system in failed state.
α_i, i =1,2,3,4,5	Mean failure rate in Ai, H,L
β_i, i=1,2,3,4,5	Mean rate of repairs in Ai, H, L.
d/dt	Represents derivative w.r.t. time 't'

3. MATHEMATICAL MODELING OF THE UREA SYNTHESIS SYSTEM

The mathematical modeling is done using simple probabilistic considerations and differential equations are developed using Markov birth-death process. If the state of the system is probability based, then the model is a Markov probability model. The present availability analysis is concerned with a discrete-state continuous-time model, is also called a Markov process. Markov model is defined by a set of probabilities p_{ij} where p_{ij} is the probability of transition from any state i to any state j. For example, the equipment transits from operable state (i) to failed state (j) with probability P_{ij}. One of the most important features of the Markov process is that the transition probability p_{ij}; depends only on states i and j and is completely independent of all past states except the last one, state i (Srinath 1994).

The objective here is to obtain an expression for the probability of n occurrences in time t. Let the probability of n occurrences in time t be denoted by $P_n(t)$, i.e., Probability (X = n, t) = $P_n(t)$ (n = 0, 1, 2, . .). Then, P_0 (t) represents the probability of zero occurrences in time t. The probability of zero occurrences in time (t + Δt) is given by

$$P_0(t+\Delta t) = (1-\beta\,\Delta t)P_0(t) \text{ i.e.}$$

The probability of zero occurrences in time (t + Δt) is equal to the probability of zero occurrences in time t multiplied by the probability of no occurrences in time Δt. The probability of no occurrences in time Δt is obviously given by $(1-\beta\,\Delta t)$. The probability of one occurrence in time (t + Δt) is composed of two parts, namely, (a) probability of zero occurrences in time t multiplied by the probability of one occurrence in the interval Δt and (b) the probability of one occurrence in time t multiplied by the probability of no occurrences in the interval Δt. Thus,

$$P_1(t+\Delta t) = (\alpha\Delta t)P_0(t) + (1-\beta\Delta t)P_1(t)$$

$$P_1(t+\Delta t) - P_1(t)/\Delta t = \alpha P_0(t) - \beta P_1(t)$$

$$Lt\ \Delta t \to 0$$

Or

$$d/dt\ P_1(t) + \beta P_1(t) = \alpha P_0(t)$$

$$or\quad (d/dt+\beta)P_1(t) = \alpha P_0(t) \qquad (A)$$

Using the concept in equation (A), and considering constant failures and repair rates the mathematical formulation is done using probabilistic Markov birth-death approach. The various probability considerations give the following differential equations associated with the urea synthesis subsystems and these equations are solved for determining the steady state performance of the urea synthesis system.

$$(d/dt+\sum_{i=0}^{5}\alpha_i)P_0(t)=\sum_{i=1}^{3}\beta_i P_{i+8}(t)+\beta_4 P_2(t)+\beta_5 P_1(t) \qquad (1)$$

$$(d/dt+\sum_{i=0}^{5}\alpha_i+\beta_5)P_1(t)=\sum_{i=1}^{3}\beta_i P_{i+11}(t)+\beta_5 P_6(t)$$
$$+\beta_4 P_3(t)+\alpha_5 P_0(t) \qquad (2)$$

$$(d/dt+\sum_{i=0}^{5}\alpha_i)P_2(t)=\sum_{i=1}^{3}\beta_i P_{i+14}(t)+\beta_4 P_4(t)+\beta_5 P_3(t) \qquad (3)$$

$$(d/dt+\sum_{i=0}^{5}\alpha_i+\beta_5+\beta_4)P_3(t)=\sum_{i=1}^{3}\beta_i P_{i+17}(t)$$
$$+\beta_5 P_6(t)+\beta_4 P_5(t)+\alpha_5 P_2(t)+\alpha_4 P_1(t) \qquad (4)$$

$$(d/dt+\sum_{i=0}^{5}\alpha_i+\beta_4)P_4(t)=\sum_{i=1}^{4}\beta_i P_{i+20}(t)+\beta_5 P_5(t)+\alpha_5 P_2(t) \qquad (5)$$

$$(d/dt+\sum_{i=0}^{5}\alpha_i+\beta_5+\beta_4)P_5(t)=\sum_{i=1}^{3}\beta_i P_{i+25}(t)+\beta_3 P_{27}(t)$$
$$+\beta_4 P_{40}(t)+\alpha_5 P_4(t)+\alpha_4 P_3(t)+\beta_5 P_8(t) \qquad (6)$$

$$(d/dt+\sum_{i=0}^{5}\alpha_i+\beta_5)P_6(t)=\sum_{i=1}^{3}\beta_i P_{i+27}(t)+\beta_5 P_{31}(t)$$
$$+\beta_4 P_7(t)+\alpha_5 P_1(t) \qquad (7)$$

$$(d/dt+\sum_{i=0}^{5}\alpha_i+\beta_5+\beta_4)P_7(t)=\sum_{i=1}^{3}\beta_i P_{i+31}(t)$$
$$+\beta_4 P_8(t)+\alpha_5 P_3(t)+\alpha_4 P_6(t)+\beta_5 P_{41}(t) \qquad (8)$$

$$(d/dt+\sum_{i=0}^{5}\alpha_i+\beta_5+\beta_4)P_8(t)=\sum_{i=1}^{5}\beta_i P_{i+34}(t)$$
$$+\alpha_5 P_5(t)+\alpha_4 P_7(t) \qquad (9)$$

$$(d/dt+\beta_m)P_i(t)=\alpha_m P_j(t) \qquad (10)$$

Where in equation (10), for
m =1: then,
i = 9,j =0; i =12,j =1; i =15,j =2; i =18, j =3;i =21, j =4; i =25,j =5; i =28,j =6; i =32,j =7; i =35,j =8
m =2: then,
i = 10,j =0; i =13,j =1; i =16,j =2; i =19, j =3; i =22, j = 4; i =26, j =5; i =29,j =6; i =33,j =7; i =36,j =8
m=3: then,
i = 11,j =0; i =14,j =1; i =17,j =2; i =20, j =3;i =23, j =4; i =27, j =5; i =30,j =6; i =34,j =7; i =37, j =8
m=4: then,
i =24,j =4; i =40,j =5; i =39,j =8
m=5: then,
i =31,j =6; i =41,j =7; i =38,j =8

3.1 Solution of Equations

With the initial condition $P_0(0)=1$, otherwise zero since any urea plant is a process industry where raw material is processed through various subsystems continuously till the final product is obtained. Thus, the long run availability of the urea synthesis system of an urea plant is attained by putting derivative of all probability equal to zero as

$$d/dt = 0 \qquad at \quad t\to\infty$$

into differential equations, one gets,

$$P_i = (\alpha_m/\beta_m)P_j \qquad (11)$$

By putting the values of probabilities from equations 11 in equations 1-9, one can represents

$C1P_0=\beta_5P_1+\beta_4P_2$	$C1=\alpha_5+\alpha_4$	(12)
$C2P_1=\beta_5P_6+\beta_4P_3+\alpha_5P_0$	$C2=C1+\beta_5$	(13)
$C3P_2=\beta_5P_3+\alpha_4P_0+\beta_4P_4$	$C3=C1+\beta_4$	(14)
$C4P_3=\alpha_4P_1+\alpha_5P_2+\beta_5P_7+\beta_4P_5$	$C4=C3+\beta_5$	(15)
$C5P_4=\beta_5P_5+\alpha_4P_2$	$C5=\alpha_5+\beta_4$	(16)
$C6P_5=\beta_5P_8+\alpha_4P_3+\alpha_5P_4$	$C6=C5+\beta_5$	(17)
$C7P_6=\beta_4P_7+\alpha_1P_1$	$C7=\alpha_4+\beta_5.$	(18)
$C8P_7=\beta_4P_8+\alpha_4P_6+\alpha_5P_3$	$C8=C7+\beta_4$	(19)
$C9P_8=\alpha_4P_7+\alpha_5P_5$	$C9=\beta_5+\beta_4$	(20)

3.2 Solving these equations recursively

P_1=C17 P_0 C17= C14+C15+C16 / (1+C12) + C11/ (C13/(1+C12)+C10 (21)

P_2 =C19 P_0 C19= (C1- (β_5*C16))/ß4 (22)

P_3=C18 P_0 C18= (C13/(1+C12)*C17)-C16 (23)

P_4=C21 P_0 C21= ((C3*C19)-α_4- (β_5*C18))/C3 (24)

P_5=C22 P_0 C22= ((C5*C21)-(α4*C19))/ß5 (25)

P_6=C20 P_0 C20= ((C2*C17)-α_5-(β_4*C18))/β_5 (26)

P_7=C23 P_0 C23 = ((C7*C20)-(α_5*C17))/β_5 (27)

P_8=C24 P_0 C24= ((α_4*C23)+(α_5*C22)) (28)

C31= (α_4/ C4) – (α_5*C5)/(C4*β4)) +(((C7*C2) + (α5* β5)) / β4) - C5+ α4

C10=1/(1+C7*β_4+((β_4*C5)/C3))*C31

C32 = ((C7*α_5) / β_4) + (α_5*C1)- (((β_4* C5*α_4) /C3)-(C5*C1)) /β_5

C11=1/(1+C7*β_4+((β_4*C5)/C3))*C32

C12= (C8*C7)/ (α_5*α_7)+(α_4*β_4) / (α_5*β_5)-(α_5*C5) / C3- (β_4*α_4) / ((α_5* β_5* C9))) * ((C4+((β_4*C5)/C3)))

C13= (C2 / (α_5* β_5)) * (((C8 *C7*β_5) / β_4) - (α_4))-((C8 / β4) + ((α_5*α_4) / β_4) + (α_4 / C9))

C14= (1/ (β_4*β_5)) * ((C8*C7) + (C1*α5*α4))

C15= ((α_4*β_4*β_4) / (β_5*β_5*C9*α_5)) * ((α_5*C5) / C3 -C1)

C16= (α_4/β_5)* (1+ ((α_5*C5) / C3) + (C1/C9))

The probability of full working capacity, namely, P_0 is determined by using normalizing condition: (i.e. sum of the probabilities of all working states, reduced capacity and failed states is equal to 1)

$$\sum_{i=0}^{41} P_i = 1 \qquad P_0*N= 1$$

Where N= (1+ C17+ C18+ C19+ C20+ C21+ C22+ C23+ C24)(1+ α_1/β_1+ α_2/β_2+ α_3/β_3)+ α_4/β_4)(1+ C21+ C24 + C22) + α_5/β_5 (1+ C20+ C24+ C23) (29)

Now, the steady state availability of desulphurization system may be obtained as summation of all working and reduced capacity state probabilities as

$$\text{Hence} \quad \text{Av.} = \sum_{i=0}^{8} P_i$$

$$\text{Av.} = P_0 + P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8$$

Av. = (1+C17+C18+C19+C20+C21+ C22+ C23+ C24)/N (30)

Therefore, Availability of the system (Av.) represents the performance model of the urea synthesis system. It can be used for developing the decision support system of this operating system of fertilizer plant.

4. DECISION SUPPORT SYSTEM

From maintenance history sheets of the urea synthesis system of fertilizer plant and through the discussions with the plant personnel, appropriate failure and repair rates of all subsystems are taken and decision matrices (availability values) are prepared accordingly by putting these failure and repair rates values in expression (30) for Availability (Av.). The decision support system deals with the quantitative analysis of all the factors viz. courses of action and states of nature, which influence the maintenance decisions associated with the urea synthesis system of fertilizer plant (Tewari, Kumar and Mehta 2000).

These decision models are developed under the real decision making environment i.e. decision making under risk (probabilistic model) and used to implement the proper maintenance decisions for the urea synthesis system. Table 1, 2, 3, and 4 represent the decision matrices for various subsystems of the urea synthesis system. These matrices simply reveal the various availability levels for different combinations of failure and repair rates/priorities. These availability values obtained in decision matrices for all subsystems are then plotted. Figures 2, 3, 4 and 5 represent the plots for various subsystems of the urea synthesis system, depicting the effect of failure /repair rate of various subsystems on ash handling unit availability. On the basis of analysis made, the best possible combinations (α, β) may be selected.

Table 1: Decision Matrix of subsystem CO_2 Booster Compressor (A1)

α_2 = 0.005, α_3= 0.01, α_4= 0.002, α_5= 0.004
β_2 = 0.1, β_3 = 0.5, β_4 = 0.1, β_5 = 0.4

	Availability (Av.) →			
α_1 \ β_1	0.1	0.2	0.3	0.4
0.005	0.9066	0.9277	0.9349	0.9336
0.025	0.7675	0.8489	0.8801	0.8965
0.05	0.6439	0.7675	0.8199	0.8489
0.1	0.4971	0.6439	0.7214	0.7675

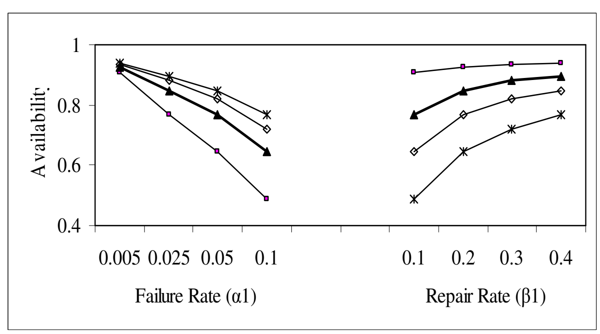


Figure 2: Effect of Failure and Repair Rates of CO_2 Booster Compressor on the Availability of the Urea Synthesis System.

Table 2: Decision Matrix of subsystem CO_2 Compressor (A2)

α_1= 0.005, α_3= 0.001, α_4= 0.002, α_5= 0.004
β_1= 0.1, β_3= 0.5, β_4= 0.1, β_5= 0.4

Availability (Av.) →				
α_2 \ β_2	0.1	0.3	0.5	0.7
0.005	0.9066	0.9277	0.9349	0.9386
0.05	0.6439	0.7675	0.8199	0.8489
0.075	0.5546	0.70	0.7675	0.8062
0.1	0.4871	0.6439	0.7214	0.7675

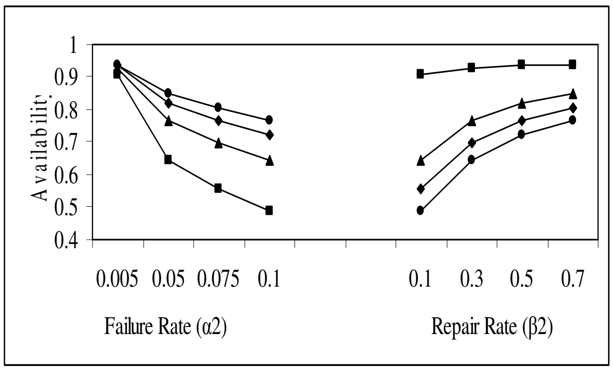


Figure 3: Effect of Failure and Repair Rates of CO_2 Compressor on the Availability of the Urea Synthesis System.

Table 3: Decision Matrix of subsystem NH_3 Preheater (A3)

α_1= 0.005, α_2= 0.005, α_4= 0.002, α_5= 0.004
β_1= 0.1, β_2= 0.1, β_4= 0.1, β_5= 0.4

Availability (Av.) →				
α_3 \ β_3	0.1	0.3	0.5	0.7
0.001	0.9000	0.9055	0.9067	0.9072
0.005	0.8688	0.8948	0.90	0.9025
0.009	0.8396	0.8842	0.8937	0.8978
0.013	0.8124	0.8739	0.8874	0.8933

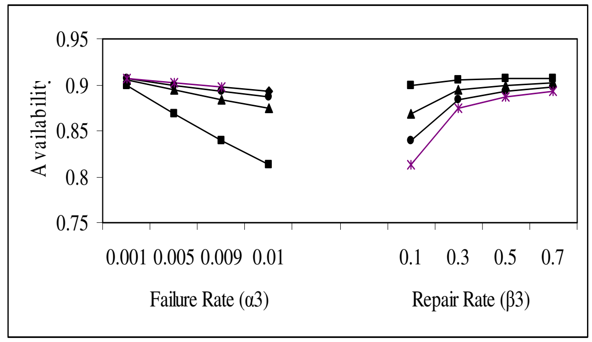


Figure 4: Effect of Failure and Repair Rates of NH_3 Preheater on the Availability of the Urea Synthesis System.

Table 4: Decision Matrix of subsystem NH_3 Feed Pump (H)

α_1= 0.005, α_2= 0.005, α_3 = 0.001, α_4= 0.002
β_1= 0.1, β_2= 0.1, β_3= 0.5, β_4= 0.1

Availability (Av.) →				
α_5 \ β_5	0.1	0.2	0.3	0.4
0.002	0.9016	0.9068	0.9070	0.9071
0.004	0.8892	0.9061	0.9066	0.9067
0.006	0.8731	0.9051	0.9061	0.9063
0.008	0.8548	0.9039	0.9057	0.9060

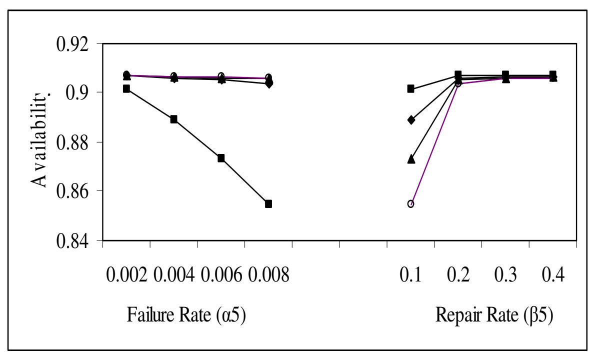


Figure 5: Effect of Failure and Repair Rates of NH_3 Feed Pump on the Availability of the Urea Synthesis System.

5. RESULTS AND DISCUSSION

Table 1 and figure 2 show the effect of failure and repair rates of CO_2 booster compressor on the availability of the urea synthesis system as failure rate of booster compressor (α_1) increases from 0.005 (once in 200 hrs) to 0.1 (once in 10 hrs), the system availability decreases significantly 41 %. Similarly as the repair rate (β_1) increases from 0.1 (once in 10 hrs) to 0.4 (once in 2.5 hrs), the system availability also increases slightly to 2.7 %.

Table 2 and figure 3 depict the effect of failure and repair rates of CO_2 compressor on the availability of the urea synthesis system as failure rate of compressor (α_2) increases from 0.005 (once in 200 hrs) to 0.1 (once in 10 hrs) ,the system availability decreases very sharply 42 %. Similarly as the repair rate (β_2) increases from 0.1 (once in 10 hrs) to 0.7 (once in 1.43 hrs), the system availability increases by 3.2 %.

Table 3 and figure 4 highlight the effect of failure and repair rates of NH_3 preheater on the availability of the urea synthesis system, as failure rate of preheater (α_3) increases from 0.001 (once in 1000 hrs) to 0.013 (once in 77 hrs), the system availability decreases considerably 8.76 %. Similarly as the repair rate (β_3) increases from 0.1 (once in 10 hrs) to 0.7 (once in 1.43 hrs), the system availability increases hardly by 1 %.

Table 4 and figure 5 explain the effect of failure and repair rates of liquid NH_3 feed pump on the availability of the urea synthesis system as failure rate of heat exchanger (α_5) increases from 0.002 (once in 500 hrs) to 0.008 (once in 125 hrs), the system availability decreases significantly 4.68 %. Similarly as the repair rate (β_5) increases from 0.1(once in 10 hrs) to 0.4 (once in 2.5 hrs), the system availability increases marginally by 1 %.

6. CONCLUSIONS

The availability model and decision support system for the urea synthesis system has been developed with the help of mathematical modeling using probabilistic approach. The decision matrices are also developed. These matrices facilitate the maintenance decisions to be made at critical points where repair priority should be given to some particular subsystem of the urea synthesis system. Decision matrix as given in table 2 clearly shows that the CO_2 compressor is most critical subsystem as far as maintenance is concerned. So, CO_2 compressor subsystem should be given top priority as the effect of its repair rates on the unit availability is much higher than that of CO_2 booster compressor, NH_3 preheater and NH_3 feed pump. Therefore, on the basis of repair rates, the maintenance priority should be gives as per following order:

1. First priority should be given to CO_2 compressor.
2. Second priority should be given to CO_2 booster compressor.
3. Third priority should be given to NH_3 preheater.
4. Fourth priority should be given to NH_3 feed pump.

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