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Original Article

Numerical Analysis of Belt Conveyors for Maintenance Decision Support System

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Abstract - *Maintaining healthy operational conditions of the belt conveyor system in a coal handling plant is a crucial requirement for all stakeholders. Unexpected failures of belt conveyors cause huge losses to the plant on production efficiency, safety and cost. It is essential to analyse the equipment conditions at an appropriate interval of time to find out the weak units that impact the plant's operational efficiency and predict their failures in time so that such losses can be eliminated through effective maintenance practices. In this study, the reliability and availability values are estimated using numerical analysis through the stochastic model. Employing the Markov process by taking the rate of failures and rate of repairs as follows the exponential distribution, the belt conveyor system is mathematically modelled. This study findings assist the plant management in identifying the critical belt conveyors that affect the system's reliability metrics and hence need focused maintenance strategies to improve their reliability and availability values. The findings will be of great importance to the plant's maintenance decision support system in the design of appropriate maintenance policies of industrial systems. Furthermore, it provides deep knowledge to future researchers for studies on the reliability of complex industrial systems.*

Keywords - *Maintenance, Decision support, State transition diagram, Reliability, Belt conveyors.*

I. INTRODUCTION

Every industry views reliability analysis of its functional systems as a vital activity for the corporate strategies to improve the output quality to remain competitive in the market and provide timely and accurate services. The system's components and equipment are prone to random failure during their regular operations due to various reasons, from increasing complexity in design changing working conditions to ineffective maintenance practices. The system must remain operational for a possibly more extended period to make the system operation viable and profitable. As failure cannot be avoided, it is required to reduce the failure chances and its impact on the system if it occurs to maintain sustainable operations [1]. System analysis for reliability and availability has been slowly recognized as standard norms for industrial systems' effective planning and efficient operation. Reliability and availability studies are done on failures and repairs of a complex system. Analysis of the reliability is appropriate in minimizing the maintenance and operational costs and improving the efficiency of system operations [2]. System components' reliability and availability significantly affect the operational efficiency of the entire system. By implementing effective reliability-based maintenance strategies, the system could meet the challenging production targets quickly and cost-effectively. To improve the system reliability, it is necessary to measure the existing reliability value of the components first to find out the weak links for corrective actions of the system.

Several studies have been done earlier to measure the reliability values of different repairable systems using different analysis models and techniques. The researchers have used qualitative and quantitative methods to evaluate the system's reliability. Reliability study has become inevitable in every stage of an industrial system from its design stage [3]. It is found that every component and equipment of the system influences the system's reliability values [4]. Analysis of every critical equipment and component of the system helps identify the system's weak link that significantly affects the system's performance [5] [6]. For the qualitative analysis, Pareto analysis and FMECA are primarily applied in formulating effective maintenance policies and design improvements in equipment to improve the system's reliability metrics, maintenance, and production costs [15]. Fault Tree Analysis (FTA), another traditional mathematical modelling tool, is proposed in determining cause and effects between simple events and complex outcomes to evaluate system reliability [16, 17, 18]. The Petri-nets method is preferred over the traditional FMECA and FTA tools in analytical modelling the system for reliability metrics utilizing the fuzzy Lambda–Tau method [19].

Monte Carlo Simulation is one of the typical quantitative analysis methods used in computing the reliability and availability of large complex systems, where analytical modelling of the system is intricate due to complexity [7, 8]. The artificial neural network (ANN) technique is explored to model a complex and repairable system's behaviours and has been trained using past data to predict the failure patterns. [9, 10]. A combination of neural

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networks (NN) and decision trees technique is explored to estimate the availability efficiency values and predict the reliability of washing machines [11]. Where the failure data of the repairable system follows a power law process, the Bayes-decision framework is used for the reliability growth model to evaluate the system reliability [12, 13]. The mathematical model was developed to predict the system's reliability subjected to Weibull failures using Simpson's rule [14]. Estimation of parameters is an extensively used modelling method for different patterns of the Weibull distribution, which produces a good fit for the reliability distribution. The reliability is calculated by fitting the failure and repair data of in different probability distributions and hence estimating the appropriate distribution parameters using analytical software tools such as Reliasoft Weibull++, Minitab, and so on, for various repairable systems such as crushing plant [20], the hydraulic system of drilling machines [6], conveyor belts of coal mine [7], conveyors of crushing plant [2], conveyor belts in a coal mine [22], conveyor system in mechanized tunnelling [23]. Time series modelling produced accurate findings for both intervals and point failure predictions regarding its prognostic performance for construction equipment reliability [24]. Even though the estimation of parameters-based analysis models is most popular and widely used by many researchers in system analysis, these models are relatively static, making them unsuitable for analysing complex repairable systems.

A few researchers explore stochastic modelling-based analysis to evaluate the reliability of some complex industrial systems. Here, the system is mathematically modelled based on the Markov process and numerically solved to find the system's steady-state probabilities, such as; feeding system of the paper industry [25], bleaching system in the paper plant [26], and un-caser system in brewery plant [27]. When the rate of failures and repairs of the subunits remain constant, the Markov models-based analysis technique is best suited as the rates are much more relevant and work well with the system [28]. It is observed from the above review of works of literature that no study has been found for reliability analysis on the large-scale, complex belt conveyor system using the stochastic modelling-based Markov approach. In this study, the authors have proposed for the belt conveyor system the Markov process-based stochastic model for analysis of the reliability considering this method's estimation abilities of multi-states system and its accuracies. The system's reliability is estimated based on rates of failure and repair of different segments of the belt conveyors. The belt conveyor system is the most complex sub-system of the Coal Handling Plant. Any failure of the belt conveyor system results in substantial financial losses to the plant.

II. COAL HANDLING PLANT (CHP)

Wagon pusher, Wagon tippler, Silos, Crusher house, Belt conveyor system etc., are the major functional subsystems in a Coal Handling Plant. Failure frequency analysis of major functional subsystems of the CHP carried out through the Pareto principle to find their respective impacts on the performance statistics of the CHP is shown in Fig. 1.

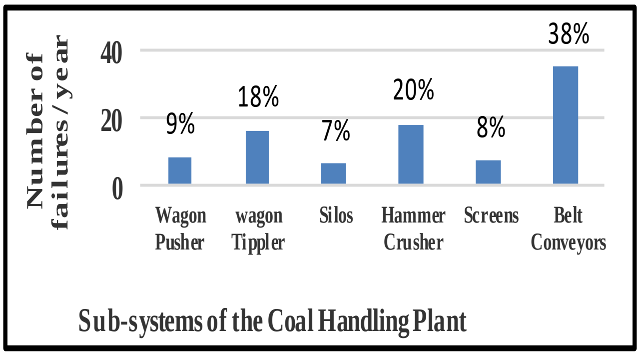


Fig. 1 Failure characteristics of systems of the CHP

The above analysis reveals that the belt conveyor system experiences the highest failures in a year than any other sub-system. 38% of the plant breakdowns happened due to failures in belt conveyors. Given the importance of keeping the belt conveyors in operations, the present study is undertaken on the belt conveyor system of the coal handling plant for its reliability analysis.

A. Belt Conveyor System (BCS):

The Belt Conveyor System of the CHP consists of twenty-three separate belt conveyors, divided into six belt segments (as S1, S2, S3, S4, S5, S6) is organized in series and parallel configurations for effective coal transportation in the plant. Fig. 2 depicts the block diagram representing the flow of coal in the coal handling plant.

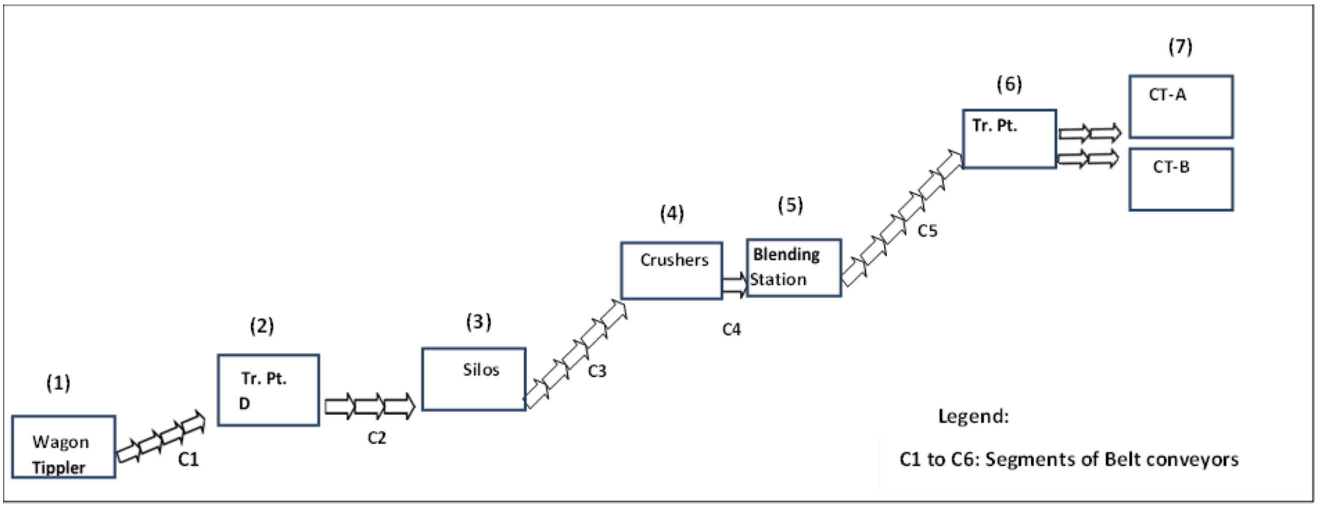


Fig. 2 Block diagram of the flow of coal in coal handling plant

B. Belt Conveyor System (BCS)

The six segments of the belt conveyors on which the mathematical modelling of the BCS is done are as follows:

a) Segment S1 Conveyors

This *Wagon un-loading* segment of conveyors transfers the coal from the wagon tippler station to the transfer point- D. This segment of conveyors consists of four individual belt conveyors placed in sequence, and failure of anyone causes the system to stop.

b) Segment S2 Conveyors

This *Silo feeding* segment of conveyors transport coal from transfer point- D to Silos. This segment consists of three separate belt conveyors placed in sequence, and failure of any of the belts causes the system to stop.

c) Segment S3 Conveyors

This *Crusher feeding segment* transfer coal from Silos to the Crusher house. It consists of five separate belt conveyors connected in a sequence, and failure of any one of them causes the system to stop.

d) Segment S4 Conveyor

This Blending segment conveyor transfers crushed coal from the crusher house to the coal blending station. It comprises one long conveyor belt, and Failure of this conveyor belt causes the system to stop.

e) Segment S5 Conveyors

This *Common-route segment of conveyors* transfer the coal from the blending station to transfer point- Y. It consists of six separate belt conveyors connected in a sequence. Failure of any one of the conveyor belts causes the system to Stop.

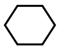
f) Segment S6 Conveyors

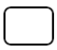
This *Coal-tower feeding* segment of conveyors transfer coal from transfer point- Y to Coal-towers A (or) B of the coke-oven batteries. It consists of two tracks of conveyors (one working and one standby) that runs in parallel. Each track of conveyors is capable of feeding the coal to anyone of the Coal Tower A (or) B alternatively. When both the tracks of conveyors fail only then the system is forced to stop

State transition diagram with assumptions and nomenclatures specified below is used in deriving the model of the system using the probabilistic approach:

- All belt Segments of the belt conveyor system are initially operating.
- The failure/repair characteristics of the systems are associated with exponential distributions.
- In terms of efficiency, a repaired belt Segment performs just as well as a new Segment.
- A standby belt Segment instantaneously replaces the failed main Segment
- The rate of failures and repairs are statistically distinct and remain stable over time.
- There are only two possible states for the system at any point in time: Working or Failed.

 : System in working state with all main segments

 : System in working state with stand-by segment

 : System in a failed state

S1, S2, S3, S4, S5 & S6	Working states of respective belt Segments
S_s6	Working state of belt Segment S6 with stand-by unit
$\underline{S1}$, $\underline{S2}$, $\underline{S3}$, $\underline{S4}$, $\underline{S5}$ & $\underline{S6}$	Failed states of respective belt Segments
$P_k(t)$, k=0,1, 2,..., 11	The probability that the system at the time (t) is in k^{th} state
λ_i, i =1-6	The mean rate of failure of belt Segment S1 to S6, respectively
μ_i, i = 1-6	Belt segments' (S1 to S6) mean repair rate
Δ_t	Time increment

Transition diagram for all states of the system as formulated and presented in Fig. 3.

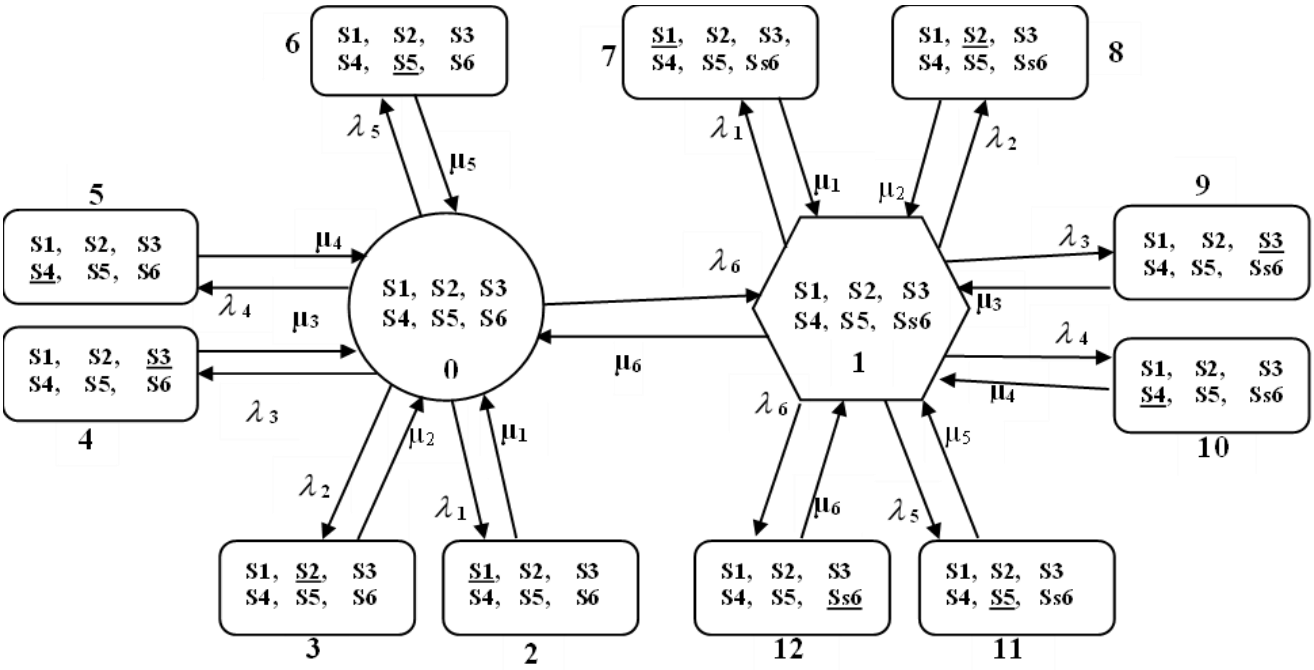


Fig. 3. Transition diagram of BCS

This system consists of two working states, namely State 0 and State1 and eleven failed states, namely State 2 to State 12. As segment S6 has a parallel system, when the main belt segment S6 fails, the system shifts to another working State1 with the standby unit, i.e., Ss6. The rate of failure is represented by λ, and the rate of repair is represented by μ.

III. SIMULATION OF THE SYSTEM

The BCS is modelled mathematically for the six segments following the Markov process to evaluate the system's reliability and steady-state availability for states, i.e., transient and steady-state.

A. Transient State Formulation

The mnemonic rule is used here to create differential equations for all possible states of the system. Probability considerations on the state transition diagram help to derive a system of differential equations at the time (t+ Δt) are generated as follows:

$$P0\ (t+\triangle t) = [1- \lambda_1\triangle t - \lambda_2\triangle t - \lambda_3\triangle t - \lambda_4\triangle t - \lambda_5\triangle t - \lambda_6\triangle t]\ P_0\ (t) + \mu_1\triangle t\ P_2(t) + \mu_2\triangle t\ P_3(t) + \mu_3\triangle t\ P_4(t) + \mu_4\triangle t\ P_5(t) + \mu_5\triangle t\ P6(t) + \mu_6\triangle t\ P_1(t)$$

By rearranging the above equation and dividing both the sides by Δ_t, we get for state 0;

$$P0\ (t+\triangle_t) - P0\ (t) / \triangle_t = [-\lambda 1 - \lambda 2 - \lambda 3 - \lambda 4 - \lambda 5 - \lambda 6]\ P0\ (t) + \mu 1\ P2(t) + \mu 2\ P3(t) + \mu 3\ P4(t) + \mu 4\ P5(t) + \mu 5\ P6(t) + \mu 6\ P1(t)$$

By taking $\Delta_t \rightarrow 0$ and re-arranging, the above equation is obtained as,

$$[\frac{d}{dt}+X1]\ P0\ (t) = \mu 1\ P2\ (t) + \mu 2\ P3\ (t) + \mu 3\ P4\ (t) + \mu 4\ P5\ (t) + \mu 5\ P6\ (t) + \mu 6\ P1\ (t) \quad (1)$$

Where, $X1= \lambda 1 + \lambda 2 + \lambda 3 + \lambda 4 + \lambda 5 + \lambda 6$

Similarly, for state 1;

$$[\frac{d}{dt}+X2]\ P1(t) = \mu 1\ P7(t) + \mu 2\ P8(t) + \mu 3\ P9(t) + \mu 4\ P10(t) + \mu 5\ P11(t) + \mu 6\ P12(t) + \lambda 6\ P0(t) \quad (2)$$

Where, $X2= \lambda 1 + \lambda 2 + \lambda 3 + \lambda 4 + \lambda 5 + \lambda 6 + \mu 6$

Similarly for state 2 to state 12, the equations are formed *as*,

$$\frac{d}{dt}P2(t) + \mu 1\ P2(t) = \lambda 1\ P0(t) \quad (3)$$
$$\frac{d}{dt}P3(t) + \mu 2\ P3(t) = \lambda 2\ P0(t) \quad (4)$$
$$\frac{d}{dt}P4(t) + \mu 3\ P4(t) = \lambda 3\ P0(t) \quad (5)$$
$$\frac{d}{dt}P5(t) + \mu 4\ P5(t) = \lambda 4\ P0(t) \quad (6)$$
$$\frac{d}{dt}P6(t) + \mu 5\ P6(t) = \lambda 5\ P0(t) \quad (7)$$
$$\frac{d}{dt}P7(t) + \mu 1\ P7(t) = \lambda 1\ P1(t) \quad (8)$$
$$\frac{d}{dt}P8(t) + \mu 2\ P8(t) = \lambda 2\ P1(t) \quad (9)$$
$$\frac{d}{dt}P9(t) + \mu 3\ P9(t) = \lambda 3\ P1(t) \quad (10)$$
$$\frac{d}{dt}P10(t) + \mu 4\ P10(t) = \lambda 4\ P1(t) \quad (11)$$
$$\frac{d}{dt}P11(t) + \mu 5\ P11(t) = \lambda 5\ P1(t) \quad (12)$$

$\frac{d}{dt}P12(t) + \mu 6\ P12(t) = \lambda 6\ P1(t)$ (13)

With Initial Conditions:

$P0\ (t) = 1$, when t=0 and 0, otherwise (14)

The derived differential equations (1) to (13) with the initial condition equation (14) are solved in the Runge-Kutta 4th order method. Accordingly, the calculations have been done at the time (t) at 0 days to 360 days for different rates, i.e., λ and μ. The system's reliability, R (t), is calculated by:

$R\ (t) = P_0\ (t) + P_1\ (t)$ (15)

B. Steady-State Formulation

To estimate the system's state probabilities, derivative of probabilities of all states are to be made equal to 0 as the system reaches the long-term availability. Hence assigning d/dt = 0, as $t \rightarrow \infty$, the derived equations (1) to (13) are shortened and then solved recursively to obtain the state probabilities w.r.t., P_0 as follows:

$P1 = (\lambda 6/\mu 6)\ P0$ (16)
$P2 = (\lambda 1/\mu 1)\ P0$ (17)
$P3 = (\lambda 2/\mu 2)\ P0$ (18)
$P4 = (\lambda 3/\mu 3)\ P0$ (19)
$P5 = (\lambda 4/\mu 4)\ P0$ (20)
$P6 = (\lambda 5/\mu 5)\ P0$ (21)
$P7 = (\lambda 1/\mu 1)\ P1$ (22)
$P8 = (\lambda 2/\mu 2)\ P1$ (23)
$P9 = (\lambda 3/\mu 3)\ P1$ (24)
$P10 = (\lambda 4/\mu 4)\ P1$ (25)
$P11 = (\lambda 5/\mu 5)\ P1$ (26)
$P12 = (\lambda 6/\mu 6)\ P1$ (27)

Using the normalising form, i.e., by equating the sum of all the state probabilities of the system to 1, the state probability P_0 is calculated. So,

$P_0 + P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 + P_9 + P_{10} + P_{11} + P_{12} = 1$ (28)

Now, by putting the values of P_1 to P_{12} from equations (16) to (27) respectively in equation (28) and by rearranging,

$P0 + P0\ ((\lambda 6/\mu 6) + (\lambda 1/\mu 1) + (\lambda 2/\mu 2) + (\lambda 3/\mu 3) + (\lambda 4/\mu 4) + (\lambda 5/\mu 5)) + P0\ (\lambda 6/\mu 6)\ [(\lambda 6/\mu 6) + (\lambda 1/\mu 1) + (\lambda 2/\mu 2) + (\lambda 3/\mu 3) + (\lambda 4/\mu 4) + (\lambda 5/\mu 5)] = 1$ (29)

If, $K = ((\lambda_6/\mu_6) + (\lambda_1/\mu_1) + (\lambda_2/\mu_2) + (\lambda_3/\mu_3) + (\lambda_4/\mu_4) + (\lambda_5/\mu_5))$ (30)

The summation of all working state probabilities provides the system with steady-state availability (A (∞)). Hence,

$A\ (\infty) = P0 + P1$ (31)
$A\ (\infty) = P0\ (1 + \lambda 6/\mu 6)$ (32)

The equation (32) is used for estimating the system availability of the belt conveyor system for different rates of failure and repair for every belt Segment of the system.

IV. SYSTEM ANALYSIS

The steady-state availability and the system reliability are computed at multiple combinations of the rate of failures and repairs of belt segments of BCS.

A. Steady-State Availability

Using the equation (32), the system steady-state availability (A (∞)) is computed at varied groupings of the rates of failure (λ) and repair (μ) of the belt segments are tabulated in Tables 1–6:

a) Effect of rates of failure and repair of belt Segments S1 and S2:

The effect of belt segment S1 on the system's steady-state availability is analysed by altering the rate of failures (λ_1) as 0.004, 0.005, 0.006 and 0.007 and the rate of repair (μ_1) as 0.1, 0.2, 0.3 and 0.4. Where, the rates of failure and rates of repair of the remaining belt segments are unchanged as, $\lambda_2 = 0.0015$, $\lambda_3 = 0.0034$, $\lambda_4 = 0.0008$ $\lambda_5 = 0.015$, $\lambda_6 = 0.003$ and $\mu_2 = 0.175$, $\mu_3 = 0.3$, $\mu_4 = 0.35$, $\mu_5 = 0.3$, $\mu_6 = 0.187$. The values obtained for belt segment S1 as above are given in Table 1 explains that the steady-state availability reduces from 2.7% to 0.7 % with the rise in the rates of failure (λ_1) from 0.004 to 0.007 and increases from 2.8% to 4.8% with the rise in the repair rate (μ_1) from 0.1 to 0.40.

Table 1. Impact of the rates of failure and repair of Belt Segment S1 on steady-state availability

λ_1 \ μ_1	0.1	0.2	0.3	0.4
0.004	0.8989218	0.9153789	0.9209993	0.9238355
0.005	0.8909132	0.9112084	0.9181805	0.9217067
0.006	0.8830460	0.9070757	0.9153789	0.9195878
0.007	0.8753166	0.9029804	0.9125943	0.9174785

The effect of belt segment S2 on the system's steady-state availability is explored by altering the failure rate (λ_2) as 0.001, 0.0013, 0.0015 and 0.0018 and the repair rate (μ_2) as 0.125, 0.15, 0.175 and 0.2. Here, the rates of failure and rates of repair of remaining belt segments are unchanged as, $\lambda_1 = 0.006$, $\lambda_3 = 0.0034$, $\lambda_4 = 0.0008$ $\lambda_5 = 0.015$, $\lambda_6 = 0.003$ and $\mu_1 = 0.3$, $\mu_3 = 0.3$, $\mu_4 = 0.35$, $\mu_5 = 0.3$, $\mu_6 = 0.187$. Similarly, the values obtained for the belt segment S2 as above given in Table 2 indicates that the system's steady-state availability reduces from 0.6% to 0.4% with the rise in the rate of failure (λ_2) from 0.001 to 0.0018 and rises from 0.3% to 0.5% with the rise in the rates of repair (μ_2) from 0.125 to 0.20.

Table 2. Impact of the rates of failure and repair of Belt Segment S2 on system steady-state availability

λ_2 \ μ_2	0.125	0.15	0.175	0.2
0.001	0.9158580	0.9169777	0.9177792	0.9183813
0.0013	0.9138493	0.9152991	0.9163375	0.9171179
0.0015	0.9125150	0.9141834	0.9153789	0.9162776
0.0018	0.9105210	0.9125150	0.9139447	0.9150199

b) Effect of rates of failure and repair of belt Segments S3 and S4

The effect of belt segment S3 on the system's steady-state availability is analysed by modifying the rate of failure (λ_3) as 0.0027, 0.003, 0.0034 and 0.0037 and the rate of repair (μ_3) as, 0.15, 0.225, 0.3 and 0.375. Where, the rates of failure and rates of repair of remaining belt segments are unchanged as, λ_1 = O.006, λ_2 = O.0015, λ_4 = O.0008 λ_5 = O.015, λ_6 = O.003 and μ_1 = O.3, μ_2 = O.175, μ_4 = O.35, μ_5 =O.3, μ_6 = O.187. The findings shown for belt segment S3 as above are given in Table 3 indicate that the system's steady-state availability reduces from 0.61% to 0.25% with the rise in the rate of failure (λ_3) from 0.0027 to 0.0037 and increases from 1.0% to 1.4% with the rise in the rate of repair (μ_3) from 0.15 to 0.375.

Table 3. Impact of the rates of failure and repair of Belt Segment S3 on system steady-state availability

λ_3 \ μ_3	0.15	0.225	0.3	0.375
0.0027	0.9098267	0.9148206	0.9173382	0.9188555
0.003	0.9081741	0.9137061	0.9164975	0.9181805
0.0034	0.9059800	0.9122243	0.9153789	0.9172821
0.0037	0.9043414	0.9111162	0.9145418	0.9166095

The effect of belt segment S4 on the system's steady-state availability is explored by altering the rates of failure (λ_4) as 0.0006, 0.0007, 0.0008 and 0.0009 and the rate of repair (μ_4) as, 0.2, 0.275, 0.35 and 0.425. Where the rates of failure and rates of repair of remaining belt segments are unchanged as, λ_1 = O.006, λ_2 = O.0015, λ_3 = O.0034 λ_5 = O.015, λ_6 = O.003 and μ_1 = 0.3, μ_2 = O.175, μ_3 = O.3, μ_5 = O.3, μ_6 = O.187. The findings shown in Table 4 indicate that the system's steady-state availability reduces from 0.14% to 0.06% with the rise in the rate of failure (λ4) from 0.0006 to 0.0009 and increases from 0.15% to 0.22% with the rise in the rate of repair (μ4) from 0.2 to 0.425.

Table 4. Impact of the rates of failure and repair of Belt Segment S4 on system steady-state availability

λ_4 \ μ_4	0.2	0.275	0.35	0.425
0.0006	0.9147808	0.9154660	0.9158580	0.9161118
0.0007	0.9143626	0.9151613	0.9156184	0.9159144
0.0008	0.9139447	0.9148569	0.9153789	0.9157170
0.0009	0.9135273	0.9145526	0.9151396	0.9155198

c) Effect of rates of failure and repair of belt Segments S5 and S6:

The effect of belt segment S5 on the system's steady-state availability is analysed by altering the failure rate (λ_5) as 0.005, 0.01, 0.015 and 0.02 and the rate of repair (μ_5) as 0.1, 0.2, 0.3 and 0.40. However, the rates of failure and rates of repair of remaining belt segments are maintained unchanged as, λ_1 = O.006, λ_2 = O.0015, λ_3 = O.0034 λ_4 = O.0008, λ_6 = O.003 and μ_1 = O.3, μ_2 = O.175, μ_3 = O.3, μ_4 =O.35, μ_6 = O.187. The findings shown in Table 5 indicate that the system's steady-state availability reduces from 12.07% to 3.43% with the rise in the rate of failure (λ_5) from 0.005 to 0.02 and increases from 3.55% to 13.73% with the rise in the rate of repair (μ_5) from 0.1 to 0.40.

Table 5. Impact of the rates of failure and repair of Belt Segment S5 on system steady-state availability

λ_5 \ μ_5	0.1	0.2	0.3	0.4
0.005	0.91537891	0.9368175	0.9441886	0.9479178
0.01	0.875316593	0.9153789	0.9295606	0.9368175
0.015	0.838613957	0.8948996	0.9153789	0.9259741
0.02	0.80486539	0.8753166	0.9016235	0.9153789

The effect of belt segment S6 on the system's steady-state availability is analysed by altering the rate of failure (λ_6) as 0.002, 0.0025, 0.003 and 0.0035 and the rate of repair (μ_6) as, 0.125, 0.156, 0.187 and 0.218. However, the rates of failure and the rates of repair of remaining Segments are maintained unchanged as, λ_1 = O.006, λ_2 = O.0015, λ_3 = O.0034 λ_4 = O.0008, λ_5 = O.015 and μ_1 = O.3, μ_2 = O.175, μ_3 = O.3, μ_4 = O.35, μ_5 = O.3. The findings shown in Table 6 indicate that the system's steady-state availability reduces from 0.047% to 0.016% with the rise in the rates of failure (λ_6) from 0.002 to 0.0035 and increases from 0.015% to 0.047% with the rise in the rates of repair (μ_6) from 0.002 to 0.0035.

Table 6. Impact of the rates of failure and repair of Belt Segment S6 on system steady-state availability

λ_6 \ μ_6	0.125	0.156	0.187	0.218
0.002	0.9153800	0.9154552	0.9154963	0.9155213
0.0025	0.91526258	0.9153794	0.9154434	0.9154822
0.003	0.91511991	0.9152871	0.9153789	0.9154346
0.0035	0.91495232	0.9151787	0.9153030	0.9153786

B. Reliability Analysis

The reliability explains the probability of performing the necessary function for a specific duration under some operating conditions. A numerical method is used here to resolve the system of differential equations derived for system reliability computations using the equation (15) for different choices of rates of failure and repair. Similarly, mean-time-between-failures (MTBF), a vital reliability metric that indicates the average time taken between failures of a repairable system, measured in the unit of hours, is also calculated using the Simpsons 1/3rd rule.

Computed reliability values of only four major belt segments such as S1, S2, S5, S6 are respectively shown in Tables 7-10 and discussed due to the paucity of space here in this report, even though the reliability values of the belt segments S3 and S4 are also computed**.** Mathematical values of the rates of failure and repair of the belt segments are estimated from the field failure and repair data, noted down from the equipment maintenance log register of the Coal Handling Plant for three years.

a) Impact of the rate of failure and repair of belt Segment S1 on the system reliability

The impact of the rate of failure of belt segment S1 (λ_1) on the system's reliability is studied by modifying the value as 0.004, 0.005, 0.006, and 0.007 at $\mu 1$= 0.3. Where, the rates of failure and rates of repair of the remaining belt segments are unchanged as, λ_2 = O.001 λ_3 = O.0027, λ_4 = O.0006 λ_5 = O.005, λ_6 = O.002 and μ_2 = O.125, μ_3 = O.15, μ_4 = O.2, μ_5 = O.1, μ_6 = O.125. It is found that the reliability value of the system reduces by 0.22% as time rises. Similarly, when the rate of failure (λ_1) rises, the reliability reduces by 0.91%, and the MTBF of the system decreases by 0.90%.

Similarly, the system's reliability is analyzed by altering the rate of repair (μ_1) as 0.1, 0.2, 0.3, and 0.4 at λ_1= 0.006. Where, the rates of failure and rates of repair of the remaining belt segments are maintained unchanged as, λ_2 = O.001, λ_3 = O.0027, λ_4 = O.0006, λ_5 = O.005 λ_6 = O.002 and μ_2 = O.125, μ_3 = O.15, μ_4 = O.2, μ_5 = O.1, μ_6 = O.125. It is observed that the system's reliability reduces by 0.39% as time rises. Similarly, when the rates of repair ($\mu 1$) rise from 0.1 to 0.4, the reliability increases by 3.8% and the MTBF of the system increases by 3.9%. The reliability values, along with the MTBF values of the system, are computed for the rates of failure (λ_1), and rates of repair (μ_1) of the belt segment S1 are illustrated in Table 7.

Table 7. Impact of the rates of failure and repair of Belt Segment S1 on the system reliability

Time (t)	Reliability - S1 Segment				Reliability – S1 Segment			
(Days)	Failure rates (λ1)				Repair Rate (μ1)			
	0.004	0.005	0.006	0.007	0.1	0.2	0.3	0.4
30	0.91730524	0.914500761	0.911716116	0.90894843	0.881172159	0.903454925	0.911716116	0.915909575
60	0.915338006	0.91255357 1	0.909786026	0.907035219	0.877882987	0.901581219	0.909786026	0.913944013
90	0.91526358 9	0.912479723	0.90971274	0.906962487	0.87777306	0.901511497	0.90971274	0.913869548
120	0.915260485	0.91247664	0.909709677	0.906959444	0.877769102	0.901508564	0.909709677	0.913866443
150	0.915260351	0.912476506	0.909709544	0.906959312	0.877768953	0.901508436	0.909709544	0.913866308
180	0.915260345	0.9124765	0.909709538	0.906959306	0.877768947	0.90150843	0.909709538	0.913866302
210	0.915260345	0.9124765	0.909709538	0.906959306	0.877768946	0.901508429	0.909709538	0.913866302
240	0.915260345	0.9124765	0.909709538	0.906959306	0.877768946	0.901508429	0.909709538	0.913866302
270	0.915260345	0.9124765	0.909709538	0.906959306	0.877768946	0.901508429	0.909709538	0.913866302
300	0.915260345	0.9124765	0.909709538	0.906959306	0.877768946	0.901508429	0.909709538	0.913866302
330	0.915260345	0.9124765	0.909709538	0.906959306	0.877768946	0.901508429	0.909709538	0.913866302
360	0.915260345	0.9124765	0.909709538	0.906959306	0.877768946	0.901508429	0.909709538	0.913866302
MTBF	320.42	319.45	318.48	317.52	307.36	315.6	318.48	319.94

b) Impact of the Failure Rate and Repair Rate of Belt Segment S2 on the System' Reliability

The impact of the rate of failure of belt segment S2 (λ_2) on the system's reliability is studied by altering the value as 0.001, 0.0013, 0.0015, and 0.0018 at $\mu 2$=0.175. Where the rates of failure and rates of repair of the remaining Segments are unchanged as, λ_1=O, it is observed that the system's reliability reduces by 0.33% as time rises. Similarly, when the rate of failure (λ_2) rises from 0.001 to 0.0018, the reliability reduces by 0.41 %, and the MTBF of the system decreases by 0.41%.

Similarly, the system's reliability is analysed by altering the rate of repair (μ_2) as 0.125, 0.15, 0.175, and 0.2 at λ_2 = 0.0015. Where, the rates of failure and rates of repair of the remaining Segments are unchanged as, λ_1 = 0.004, λ_3 = 0.0027, λ_4 = O.0006, λ_5 = O.005 λ_6 = O.002 and μ_1 = O.1, μ_3 = O.15, μ_4 = O.2, μ_5 = 0.1, μ_6 = O.125. It is observed that the system's reliability reduces by 0.34% as time rises. Similarly, when the repair rate (μ_2) rises from 0.125 to 0.2, the reliability increases by 0.38& and the MTBF increases by 0.40%. The reliability values, along with MTBF values of the belt conveyor system computed according to the rates of failure (λ_2) and rates of repair (μ_2) of the belt segment S2, are provided in Table 8.

Table 8. Impact of the rates of failure and repair of Belt Segment S2 on the system reliability

Time (t)	Reliability - S2 Segment				Reliability – S2 Segment			
(Days)	Failure rates (λ2)				Repair Rate (μ2)			
	0.001	0.0013	0.0015	0.0018	0.125	0.15	0.175	0.2
30	0.898275802	0.896890223	0.895968863	0.894590348	0.89333268	0.894846167	0.895968863	0.896827103
60	0.895390599	0.894018007	0.893105283	0.891739687	0.89037788	0.891966332	0.893105283	0.893961338
90	0.895286376	0.893914409	0.893002098	0.891637118	0.890276177	0.891864282	0.893002098	0.893857352
120	0.895282361	0.893910414	0.892998117	0.891633157	0.890272356	0.891860359	0.892998117	0.893853342
150	0.895282202	0.893910256	0.892997959	0.891632999	0.890272206	0.891860202	0.892997959	0.893853183
180	0.895282195	0.893910249	0.892997952	0.891632993	0.890272199	0.891860196	0.892997952	0.893853176
210	0.895282195	0.893910249	0.892997952	0.891632992	0.890272199	0.891860196	0.892997952	0.893853176
240	0.895282195	0.893910249	0.892997952	0.891632992	0.890272199	0.891860196	0.892997952	0.893853176
270	0.895282195	0.893910249	0.892997952	0.891632992	0.890272199	0.891860196	0.892997952	0.893853176
300	0.895282195	0.893910249	0.892997952	0.891632992	0.890272199	0.891860196	0.892997952	0.893853176
330	0.895282195	0.893910249	0.892997952	0.891632992	0.890272199	0.891860196	0.892997952	0.893853176
360	0.895282195	0.893910249	0.892997952	0.891632992	0.890272199	0.891860196	0.892997952	0.893853176
MTBF	0.00	312.99	312.67	312.19	311.72	312.27	312.67	312.97

c) Impact of the Failure Rate and Repair Rate of Belt Segment S5 on the System's Reliability

The impact of the rate of failure of belt segment S5 (λ_5) on the system's reliability is analysed by altering the value as 0.005, 0.01, 0.015, and 0.02 at μ_5 = 0.3. Whereas, the rates of failure and rates of repair of the other Segments are unchanged as, λ_1 = 0.004, λ_2 = 0.001, λ_3 = 0.0027, λ_4 = 0.0006, λ_6 = 0.002 and μ_1 = 0.1 μ_2 = 0.125, μ_3 = 0.15, μ_4 = 0.2, μ_6 = 0.125. It is observed that the system reliability reduces up to 0.19% as time rises. Similarly, when the rate of failure (λ_5) rises, the reliability reduces by 4.4%, and the MTBF of the system decreases by 4.4%.

Similarly, the system's reliability is analyzed by altering the rate of repair (μ_5) as 0.1, 0.2, 0.3, and 0.4 at λ_5= 0.015. Where the rates of failure and rates of repair of the other Segments are unchanged as, λ_1= 0.004, λ_2 = 0.001, λ_3 = 0.0027, λ_4 = 0.0006, λ_6 = 0.002 and μ_1 = 0.1, μ_2 = 0.125, μ_3 = 0.15, μ_4 = 0.2, μ_6 = 0.125. It is observed that the system reliability decreases up to 0.51% as time rises. Similarly, when the repair rate (μ_5) rises from 0.1 to 0.4, the reliability increases by 8.93%, and the MTBF increases by 9.2%. The reliability values, along with MTBF values of the belt conveyor system computed according to rates of failure (λ_5) and rates of repair (μ_5) of the belt segment S5, are shown in Table 9.

Table 9. Impact of the rates of failure and repair of Belt Segment S5 on the system reliability

Time (t)	Reliability - S5 Segment				Reliability – S5 Segment			
(Days)	Failure rates (λ5)				Repair Rate (μ5)			
	0.005	**0.01**	**0.015**	**0.02**	**0.1**	**0.2**	**0.3**	**0.4**
30	0.922621984	0.908626587	0.895050509	0.881875134	0.824378635	0.875419329	0.895050509	0.905214155
60	0.920946152	0.907023608	0.893515779	0.880404405	0.820289632	0.873988363	0.893515779	0.903609209
90	0.920882156	0.90696206	0.893456532	0.880347323	0.820178424	0.873935791	0.893456532	0.90354757
120	0.920879433	0.906959429	0.893453987	0.88034486	0.820175128	0.873933498	0.893453987	0.903544936
150	0.920879313	0.906959311	0.893453873	0.880344749	0.820175019	0.873933394	0.893453873	0.903544818
180	0.920879307	0.906959306	0.893453868	0.880344744	0.820175014	0.873933389	0.893453868	0.903544813
210	0.920879307	0.906959306	0.893453868	0.880344744	0.820175014	0.873933388	0.893453868	0.903544813
240	0.920879307	0.906959306	0.893453868	0.880344744	0.820175014	0.873933388	0.893453868	0.903544813
270	0.920879307	0.906959306	0.893453868	0.880344744	0.820175014	0.873933388	0.893453868	0.903544813
300	0.920879307	0.906959306	0.893453868	0.880344744	0.820175014	0.873933388	0.893453868	0.903544813
330	0.920879307	0.906959306	0.893453868	0.880344744	0.820175014	0.873933388	0.893453868	0.903544813
360	0.920879307	0.906959306	0.893453868	0.880344744	0.820175014	0.873933388	0.893453868	0.903544813
MTBF	322.3789181	317.5038472	312.7740667	308.1831749	287.2318309	305.9373216	312.7740667	316.308859

d) Impact of Failure Rate and Repair Rate of Belt Segment S6 on the Reliability of the System

The impact of the rate of failure of belt segment S6 (λ_6) on the system's reliability is analysed by altering the value as 0.0025, 0.003, 0.0035 and 0.004 at μ_6 = 0.187. Where the rates of failure and rates of repair of the remaining Segments are unchanged as, λ_1 = 0.004, λ_2 = 0.001, λ_3 = 0.0027, λ_4 = 0.0006, λ_5 = 0.005 and μ_1 = 0.1 μ_2 = 0.125, μ_3 = 0.15, μ_4 = 0.2, μ_5 = 0.1. It is observed that the system reliability reduces by 0.33% as time rises. Similarly, when the rate of failure (λ_6) rises, the reliability decreases by 0.023 % and the MTBF of the system decreases by 0.024%.

Similarly, the system's reliability is analyzed by altering the rate of repair (μ_6) as 0.125, 0.156, 0.187, and 0.218 at λ_6= 0.003. Where the rates of failure and rates of repair of the other Segments are unchanged as, λ_1 = 0.004, λ_2 = 0.001, λ_3 = 0.0027, λ_4 = 0.0006, λ_5 = 0.005 and μ_1 = 0.1, μ_2 = 0.125, μ_3 = 0.15, μ_4 = 0.2, μ_5 = 0.1. It is detected that the system's reliability decreases by 0.34% as time rises. Similarly, when the repair rate (μ_6) rises, the reliability rises by 0.029 %, and the MTBF rises by 0.03%. The reliability values along with MTBF values of the belt conveyor system computed according to rates of failure (λ_6), and rates of repair (μ_6) of the Segment S6 are indicated in Table 10.

Table 10. Impact of the belt segments' rates of failure and repair on the system's reliability for Belt Segment S6

Time (t)	Reliability – S6 Segment				Reliability – S6 Segment			
(Days)	Failure Rate (μ6)				Repair Rate (μ6)			
	0.0025	0.003	0.0035	0.004	0.125	0.156	0.187	0.218
30	0.896551025	0.896490236	0.896418695	0.896336494	0.896284447	0.896411682	0.896490236	0.896540937
60	0.893620346	0.893558926	0.893486633	0.89340356	0.893314852	0.893471805	0.893558926	0.89361198
90	0.893518193	0.893456775	0.893384486	0.893301416	0.893210237	0.893369364	0.893456775	0.89350986
120	0.89351437	0.893452952	0.893380662	0.893297591	0.893206223	0.893365523	0.893452952	0.893506039
150	0.893514223	0.893452805	0.893380515	0.893297444	0.893206059	0.893365374	0.893452805	0.893505892
180	0.893514218	0.893452799	0.893380509	0.893297438	0.893206052	0.893365369	0.893452799	0.893505886
210	0.893514217	0.893452799	0.893380509	0.893297438	0.893206051	0.893365368	0.893452799	0.893505886
240	0.893514217	0.893452799	0.893380509	0.893297438	0.893206051	0.893365368	0.893452799	0.893505886
270	0.893514217	0.893452799	0.893380509	0.893297438	0.893206051	0.893365368	0.893452799	0.893505886
300	0.893514217	0.893452799	0.893380509	0.893297438	0.893206051	0.893365368	0.893452799	0.893505886
330	0.893514217	0.893452799	0.893380509	0.893297438	0.893206051	0.893365368	0.893452799	0.893505886
360	0.893514217	0.893452799	0.893380509	0.893297438	0.893206051	0.893365368	0.893452799	0.893505886
MTBF	312.8537333	312.832262	312.8069905	312.7779504	312.747601	312.8020233	312.832262	312.8507463

V. DISCUSSION

Tables 1-6 provides the system's steady-state availability values calculated for different selections of rates of failure (λ_i) and the rates of repair (μ_i) of respective belt segments. Similarly, Tables 7-10 provides the system's reliability values computed at several choices of rates of failure (λ_i) and rates repair (μ_i) of major 4 belt segments. The above comparative analysis reveals that belt Segment C5, i.e., the Common route belt conveyor has the maximum impact on both the steady-state availability and reliability and hence it is identified as the critical one among the entire BCS.

The effects of failure rate (λ_5) and repair rate (μ_5) on the system's steady-state availability are depicted graphically in Fig. 4.

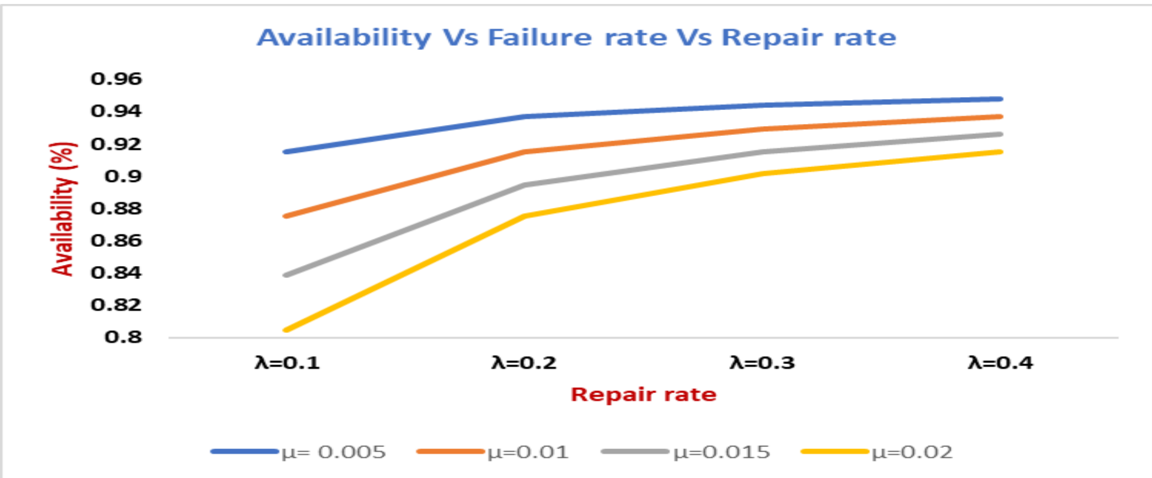


Fig. 4 Steady-state availability of the system on the effect of rates of failure and repair of belt Segment S5

Similarly, the impact of the rate failure (λ_5) and repair (μ_5) on the system's reliability, respectively, is described in Fig. 5 and Fig. 6.

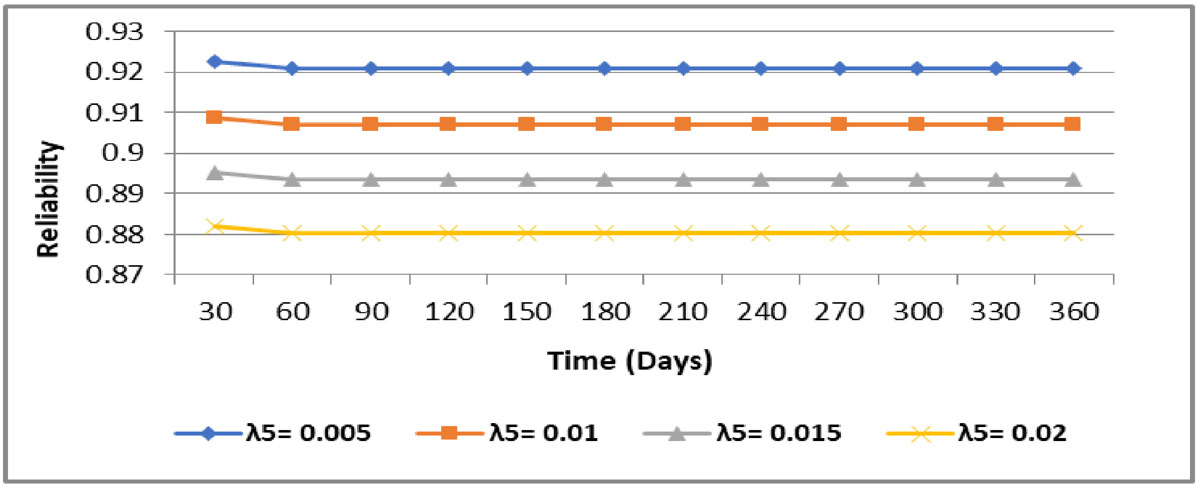


Fig. 5 Reliability of system on different rates of failure of belt Segment S5

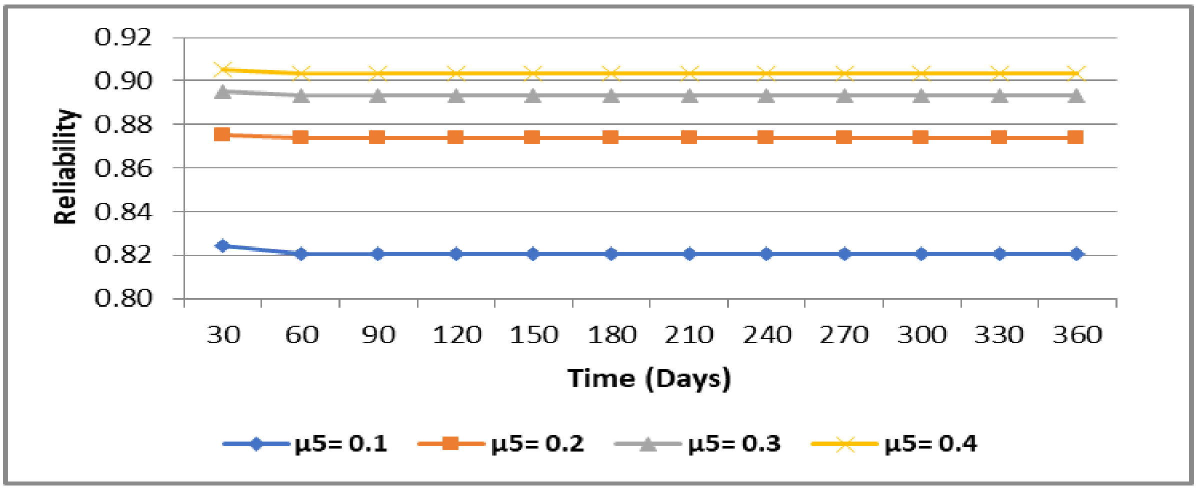


Fig. 6 Reliability of system on different rates of repair of belt Segment S5

As the belt Segment S5 has the highest effect on the system's reliability and steady-state availability, even a trivial improvement in its failure rate and repair rate will have a substantial improvement on its reliability metrics. The other belt segments also have a similar impact on the system's reliability and steady-state availability but have a lesser impact than the belt segment S5 due to their improved reliability statistics. Hence, the belt segment S5 requires more intensified attention from a maintenance point of view.

To minimize the effect of the belt segment S5 on the system's reliability metrics, the failure rate (λ_5) and repair rate (μ_5) of the belt Segment S5 should be improved through the application of efficient maintenance strategies and practices. Implementation of some redundancy arrangements to the critical belt Segment S5 through the addition of parallel belt conveyors would improve the system's reliability indexes significantly.

VI. CONCLUSION

- Markov process-based stochastic modelling is very effective in the complex belt conveyor system's reliability analysis and steady-state availability analysis.
- The proposed numerical analysis method using R-K fourth-order in solving the differential equations is very efficient for large-scale complex systems.
- Belt Segment S5 is the most critical belt segment among the entire belt conveyor system that has the highest effect on the reliability metrics of the entire system.
- The reliability metrics of the belt Segment S5 could be improved by implementing more intensive maintenance practices along with modernized control and monitoring systems.
- This study report has been deliberated with the plant's management as these findings are found to be highly valuable to the plant in the identification of the weak links in the system that need specific attention from in maintenance point of view and to improve the quality of the output and cost of production of coal handling plant.

- This study report will also serve as a trusted data source for future researchers in related research analysis on similar large-scale and complex industrial systems.

VII. CONFLICTS OF INTEREST

No potential conflict of interest was reported by the authors

VIII. ACKNOWLEDGEMENT

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