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Analyzing Reliability and Maintainability of Crawler Dozer BD155 Transmission Failure Using Markov Method and Total Productive Maintenance: A Novel Case Study for Improvement Productivity

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Abstract: Surface mining is the world's most costly industry due to its enormous expenses. Reduced production is forcing mining companies to automate their equipment, predominantly heavy earth mining machinery (HEMMs), for example, dump trucks, shovels, and dozers. The backbone of pit mining is the crawler dozer, commonly known as a dozer. Crawler dozers are tracked earth-moving machines with metal blades positioned in front for pushing materials such as rocks, soil, etc. In order to survive the harsh competition, dozers must be durable and adequately maintained. Crawler dozers work under challenging conditions to avoid production delays that result in losses such as breakdowns, transmission failures, and other issues in mining operations. Transmission failures, among other issues with dozers, are one of the hardest to resolve. This study evaluates the reliability, availability, and maintainability (RAM) of a BD155 crawler dozer transmission using failure and repair data and the Markov method. A realistic case study on (BD155) transmission failure and associated subsystems has been performed. Potential approaches and alternatives are also identified to increase dependability and performance. This article also discusses best maintenance practices for minimizing transmission failures and boosting productivity. The availability of the BD155 increases to 71% from 62% using proper planning and maintenance.

Keywords: crawler dozer; reliability; maintainability; availability; Markov model

1. Introduction

Coal is a precious resource with a mining history dating back over 225 years. India ranks as the world's third-largest coal producer. Underground and opencast or open pit coal mining are both used in India. Open pit mining dominates in India, accounting for 93.26 percent of total coal production, due to cheaper production costs, automation, and depletion. Mining companies are expected to operate their equipment as efficiently as possible to maximize output while minimizing investment and production expenses. Maintenance of dumpers, crawler dozers, and other HEMMs is complex and costly. Although the mining business has improved over time, cost, size, competitiveness, and safety remain key concerns. If machines such as dumpers, dozers, and other heavy equipment break down while in use, work stops and capital losses are inevitable [1].

A system's dependability has three primary attributes: availability, maintainability, and reliability, which have a significant influence on the overall lifetime cost of a system. Maintainability is the likelihood of returning a system to its original state following a failure. Reliability is a system's ability to perform a particular function within a specified time frame, whereas availability is preparedness for the right services, which have the quality of dependability. Dependability's integration is influenced by the degree of automation, process types, management style, and organizational atmosphere [2].

Dozers are pieces of machinery that can push and dig, and their front pushing edges can be lifted and dropped hydraulically. Dozers are typically used in open pit mines to move heavy particles to a disposal site [3]. Road cuts, ramping down, leveling the ground on the terrain, transporter movement, breaking piles, and checking ground stability are all ways to clear paths for excavators and spreaders to be transported. Due to constant operation and extreme temperatures, breakdowns, particularly transmission failures, are prevalent [4]. Transmission subsystems are prone to failure, including the torque converter, gears, power take-off, or PTO. The failure data from each transmission subsystem, such as time between failures (TBF) and time to repair (TTR), should be analyzed graphically and statistically for availability, reliability, and optimal maintenance [5]. Routine maintenance and regeneration can considerably improve transmission (BD155) reliability.

Production, maintenance, reliability assessment, problem detection, and risk assessment, among other things, all require reliability forecasting. The reliability, availability, and maintainability (RAM) of crawler dozer transmissions (BD155) have been studied using Markov modeling in this work. Various approaches have been used to investigate equipment performance to determine reliability, availability, and maintainability. The fault tree, RCM, and Markov modeling are the most common approaches. Reliability analysis is required to find tailbacks in the system and its subsystems with low reliability for a specific performance specification [6]. The RAM methodology can be highly favorable for the mining sectors due to the complexities of machinery maintenance and operation [7]. The reliability, availability, and performance of the LHD machines were analyzed by Kumar [8]. The primary goal of their investigation was to evaluate faults based on absolute data.

Morad (2014) investigated the Sungun copper mine and found that reliability-centered maintenance improves availability, production, and performance [9]. Reliability analysis has been performed on various systems and subsystems including draglines, HEMMs, etc., and performance depends upon subsystems [10]. Maintainability, reliability, and availability are all affected by subsystems, according to dragline analysis [11]. When it came to structural assembly, it was observed that bucket components had the shortest MTTF = 54 h, and dragline components had the highest MTTR = 88 h [12]. The dragline subsystem's most critical portion is the equipment with the most time for the buckets and tooth replacement and maintenance [13]. In order to achieve maximum availability, maintainability, and reliability, the subsystems of BD155 should be connected in series. As the subsystems are interlinked, failure in any one subsystem will lead to the overall failure of BD155. However, the system's availability in parallel is higher when subsystems are fully independent. Costs may rise as a result of unexpected failures and repairs. Appropriate time-calculation techniques can predict the most likely failure causes [14]. Acuna and Curilem's research focuses on MTTR and MTBF determination using nonlinear autoregressive exogenous approaches [15]. Preventive maintenance (PM) can be utilized to identify, avoid, and anticipate defects, according to Washimkar [16]. When several random and fuzzy variables are present, FRM (fuzzy reliability measure) techniques can be used to estimate the dependability of electrochemical products [17]. Probabilistic and statistical modeling was utilized to increase the reliability of mountain plowing [18]. By including the radial function, a first-order reliability method was established to forecast the reliability of tunneling activities [19]. In project management, reliability modeling and maintenance techniques can help resource allocation and production growth [20].

Markov modeling is a mathematical technique that depicts the correlation between failure and the current state. This approach creates a transition matrix that connects the

pre-failure and post-repair states. In 2016, Yunwen Xu studied traffic signals using the Markov model [21]. B. Samanta also used the Markov technique to examine the LHD's performance. He concentrated his research on making the LHD's subsystems more reliable and maintainable [22]. The road header–conveyor system in longwall mining was studied by Murthy using a Markov method [23]. Lalropuia used a continuous-time Markov technique to determine the MTTF for a cyber-physical structure's life cycle [24]. In 2016, Ossai used Markov analysis to predict the pit allocation of damaged gas line piping [25]. Anil Aggarwal (2019) also conducted experiments for the application of tunnel boring machines using Markov methodology for evaluating RAM, and it has been found that reliability, availability, and maintainability were improved. EPBTBM availability has increased from 61% to 70% with proper planning and maintenance [26]. Reliability engineering emphasizes statistical and mathematical theories, which give the fundamental tools for assessing a system's probability of failure and evaluating management and maintenance strategies to improve the system's lifetime. Fault tree analysis (FTA) and reliability block diagrams (RBDs) are the two main tools of classic theory, which typically operate in steady-state or fixed settings. Due to this constraint dynamic, research has focused on the system's dynamics and external influences (temperature, pressure, etc.). Diego D'Urso (2021) has also worked on a dynamic failure rate model of an electric model by contrasting military standards with the Svenska Kullagerfabriken (SKF) approach [27]. Geeta Yadav (2022) investigated component-wise reliability to improve the microgrid's overall reliability. Even elements are further broken into subcomponents, considering each component's various faults. Markov state transition modeling is used for the availability and reliability study. In terms of reliability, there has been an improvement of 96% [28]. Odeyar (2022) gave a thorough overview of the many statistical methods used for dependability and fault prediction in theoretical and practical contexts. Additionally, the algorithm's benefits and drawbacks are explored, and the effectiveness of novel ML techniques is contrasted with that of more conventional ones [29].

This paper highlights the value of using Markov models to assess the availability, maintainability, and reliability of a crawler dozer transmission (BD155) often used in opencast or pit mining. A reliability block diagram for several subsystems has also been provided. It also features an availability function to help create dependable and maintained expressions. The steady-state expression of availability has been obtained using the normalizing condition. The proposed research will develop a Markov model for BD155 transmission subassemblies. The MTTF and MTTR have been predicted using a stable state availability expression. In addition, total productive maintenance (TPM), in conjunction with preventative maintenance (PM), has also been utilized effectively to improve the system's reliability.

2. Research Methodology

As shown in Figure 1, a stepwise study process was established for RBD modeling and performance analysis of BD155 transmission. The BD155 transmission was explained in great detail at the outset. In the subsequent sections, we constructed a reliability block diagram (RBD) for the BD155 transmission. Markovian modeling can be employed if the RBD process satisfies the steady-state conditions; otherwise, the process becomes non-homogeneous or non-Markovian. Generally, phase-type expansions, the use of extra variables, or the creation of an embedded Markov process have been used to solve non-Markovian models. Queuing nets and randomized Petri networks have been studied concerning all three methods. The spatial structure is enlarged in the phase-type expansion strategy. In contrast, the method of extra variables and the embedded Markovian architecture demand that non-exponentially scheduled activities are not contemporaneous [30]. A Markov transition diagram is presented, along with underlying presumptions. The state transition linear differential equations for the Markov process were established using the transition diagram, and the steady-state performance of BD155 transmission was investigated afterward.

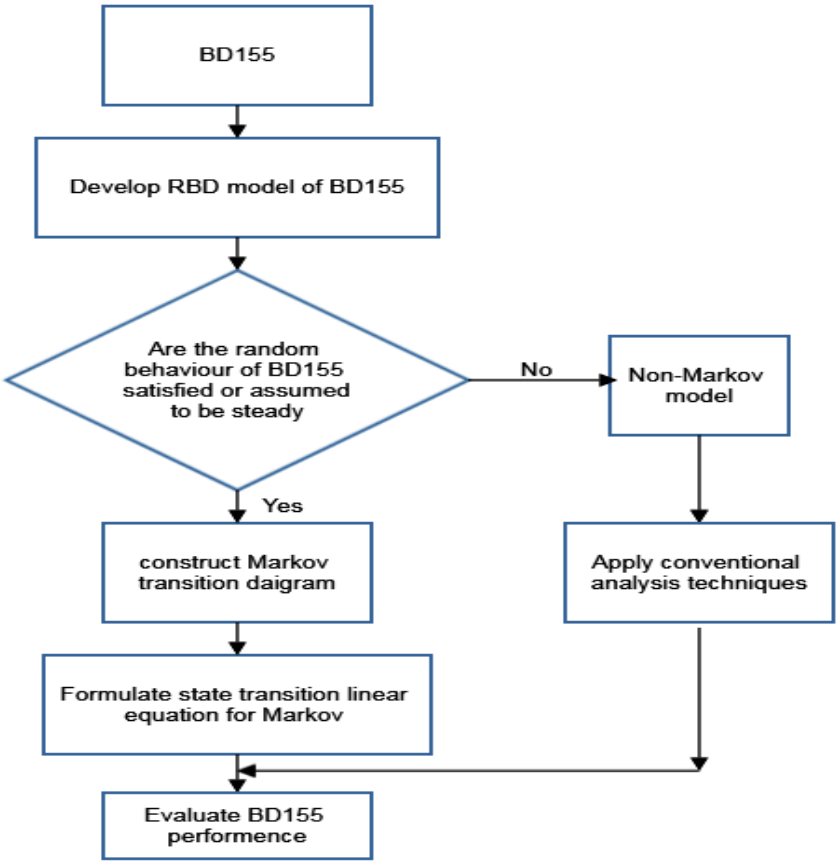


Figure 1. Flowchart for RBD modeling of BD155 transmission using Markov process.

3. BD155 Crawler Dozer Transmission: At a Glance

A crawler, sometimes apprehended as a tracked bulldozer, is specialized equipment that looks similar to a tractor. This heavyweight machine is great for transferring copious amounts of things from one place to another. Dozers are classified into two types based on transmission type: hydrodynamic and hydrostatic systems. Hydrostatic systems are emphasized due to the possibility of providing a more robust transmission (equivalent to moderate priority on the Saaty scale). With a single lever control for quick speed and direction adjustments, the BD155's hydrostatic transmission provides smooth, fast gear shifts. Table 1 shows the specifications of transmission for the BD155.

Table 1. Specifications of BD155 transmission.

Net Torque:	1456 N-m (148.5 kg-m) @ 1400 rpm		
Torque Converter:	Type 3 element, Single Stage and Single phase		
	Stall ratio: 2.4		
Transmission Type:	3F/3R, Planetary Power shift Transmission		
Final Drive:	Type-Spur gearing, Double reduction		
	Lubrication Type: Splash		
	Total Reduction: 40.104		
Speeds m/sec (km/h):	Range	Forward	Reverse
	1st	0–1.03 (0–3.07)	0–1.25 (0–4.50)
	2nd	0–1.89 (0–6.80)	0–2.30 (0–8.20)
	3rd	0–3.28 (0–11.8)	0–3.81 (0–13.7)

Maintaining transmission reliability is inevitably an exertion due to their working circumstances and environment. Used in open pit mines, the BD155 has a heavy-duty automatic transmission. The BD155 is made up of several subsystems, as seen in Figure 2. Dozer transmission (BD155) also consists of various subsystems. Accurately analyzing the complete system is difficult because the transmission of heavy mining equipment is an immensely complex structure. In this proposed study article, the transmission's key or critical subsystems, such as the hydrostatic pump, converter housing, torque converter, and planetary gears, have been picked for investigation. Transmissions comprise complex systems with many mechanical parts, but just a generous handful have been adequately addressed because they fail frequently and cause production loss.



Figure 2. BD155 transmission.

Subsystems of BD155 Crawler Dozer

The major subsystems of a BD155 crawler dozer are covered as follows:

Hydrostatic pump: The primary function of the hydrostatic pump is to convert the pressure energy of the fluid to mechanical energy. It is reconverted to mechanical energy from pressure energy using a hydraulic motor. An infinitely variable transmission (IVT) can be generated by adjusting the pump's displacement and obtaining a continual ratio from zero to the maximum value. As a result, a starting clutch is no longer required. When the pump and the motor switch roles, the direction of the torque is reversed.

Converter housing: Usually, steel is used for the torque converter housing. A splined output shaft protrudes at one end and connects to the transmission. The shaft's entrance allows new fluid to enter and old fluid to escape and cool. Transmission fluid flows via this opening. The housing's opposite end fastens to the flex plate at the motor's back, which revolves with the engine's crankshaft. Due to the housing and shaft's distinct rotational velocities, the output shaft rotates independently of the housing.

Torque converter (TC): The hydraulic TC is similar to the fluid coupling. Through the TC, the engine's torque is transmitted to a driven load that is spinning. The five fundamental components of a TC are the fluid, stator, impeller, turbine, and clutch. A torque converter is only a fluid coupling without a stator, which gives it its specific function. Oil is the power source in both. Low-speed pumps or impeller blades drive oil against the stator's blades. These blades deflect oil up against a turbine, increasing torque.

Planetary gears: A planetary gear set is composed of three different types of gear: ring gear, planet gears, and sun gears. The planet gears are typically installed on a movable carrier, and the sun gear, which is in the middle, transmits torque to them. The weight is divided among several planet gears, which allows planetary gear systems to generate much torque. When weight and space are a limitation but a significant degree of torque and speed reduction is required, planet gears are frequently employed.

4. Reliability Analysis of Dozer Transmission (BD155)

A thorough evaluation of all BD155 transmission subsystems has been performed with the help of MTTF and MTTR metrics. The stats or data needed to analyze BD155 and its subsystems are obtained from mining industry machine records and logs. Data collection has shown that, compared to other mechanical components, the subsystems above fail more frequently. Since one subsystem is connected to the others in a series, any problem in a subassembly will stop the whole operation. As a result, transmission is generally reliable. The reliability of each subcomponent will provide the overall reliability of the system. Markov modeling is used for examining the reliability of transmission subsystems.

Reliability: The probability that a product or system will function as intended for a predetermined period or run faultlessly in a specified environment is known as reliability. It is the probability of non-failure over time. The below-mentioned expression of reliability is valid for random failures, which can be modeled with exponential distribution. It can be represented as R(t).

Arithmetically, R (t) = $e^{-\lambda t}$ where λ (t) = failure rate [31]

Maintainability: The probability of a failed system or component being fixed or returned to its pre-failure state within a predetermined time frame is known as maintainability. The expression of maintainability is valid for random restorations, which can be modeled with exponential distribution. It is symbolized as M (t).

$$\mathrm{M}\ (\mathrm{t}) = 1 - e^{-\mu t} \text{ where } \mu\ (\mathrm{t}) = \text{Repair rate of BD155}$$

Availability: Availability is the probability that a system will be ready to respond when necessary. A system will likely perform as needed when the requirement is high.

$$\mathrm{A}\ (\mathrm{t}) = \frac{MTTF}{MTTF + MTTR} \text{ where, MTTF} = \text{mean time to failure, MTTR} = \text{mean time to repair}$$

4.1. Markov Modeling

The Markov method can analyze the randomized behavior of systems that change continuously or discretely through time and space. A stochastic process may be continuous or discrete. Not every stochastic process can be treated using the fundamental Markov approach. The future states of a system must be independent of every former state other than the most recent one for the fundamental Markov methodology to be applicable. The process must be stationary or homogenous for the method to work. For getting the A(t), M(t), and R(t) of the subsystem of BD155 transmission, the Markov technique is thought to be the effective way.

Arithmetically,

Now consider an incremental time interval Δt so small that the probability of more than one event occurring during it is practically zero.

$$R_{si}(t, t + \Delta t) = \sum_{zj \in \cup} P_{ij}(t) R_{sj}(\Delta t),\ where\ i = 0, 1, 2 \ldots m,\ \Delta t > 0$$

$$R_{si}(\Delta t) = \lim_{t \to \infty} Rsi\ (t, t + \Delta t) = \sum_{zj \in \cup} (t, t + \Delta t),\ \Delta t > 0$$

With

$$P_j = lim_{t \to \infty}\ P_j(t) = lim\ _{t \to \infty}\ P_{ij}\ (t)$$

From

$$\rho_j P_j = \sum_{i=0, i \neq j}^{m} P_j \rho_{ij}\ i, j\ \epsilon \{0 \ldots m\}$$

$$P_0 + P_1 + P_2 \ldots .. + P_m = 1$$

where,

S = system and U = groups of up states

R_{si} $(t, t + \Delta t)$ = *Pr* {*system up in* $[t, t + \Delta t]$, Z_i *is entered at* $t = 0$, $Z_i \in U$ (*in general*)
Rsi (Δt) = Pr {*system up in* $[t, t + \Delta t]$, *in steady-state for* $t \to \infty$
$\rho ij = \lim_{\Delta t \to 0} \frac{1}{\Delta t}$ Pr $\{(transition\ from\ Zi\ to\ Zj\ in\ (t, t + \Delta t)\}$ [31]

4.1.1. Reliability Block Diagram (RBD) of BD155 Transmission

RBDs, widely used during the system's reliability, availability, and maintainability assessments, allow us to model the failure correlations of complex processes and their subcomponents. An RBD is a graphical framework of boxes and links (lines) that demonstrate how the system's components function and are interconnected. Using the RBD analysis, we may assess how component failures affect the reliability of the entire system. Based on the component failure rates, the failure attributes of the entire system can be evaluated. Due to their ease of formulation and steady-state circumstances, RBDs and other classical theories such as fault tree analysis are frequently utilized. However, dependability results derived using these classic methods are frequently erroneous. Chiacchio (2019) deeply narrated the need for dynamic reliability in his research. The author proposed the Stochastic Hybrid Fault Tree Object Oriented (SHyFTOO) software library for modeling and resolving a SHyFTA model with a Matlab Simulink model, which makes it easier to build complex system dynamics [32].

RBD is the acronym for the graphical representation of transmission in the BD155 and its subsystem's reliability. As seen in Figure 3, the transmission of the BD155 is made up primarily of four subsystems. It is impossible to evaluate every subsystem of the BD155 due to its highly complicated structure. A few presumptions have been taken into consideration to create the transition matrix for Markov analysis. An analysis of the steady-state performance of the BD155's transmission has been performed to determine the main challenges.

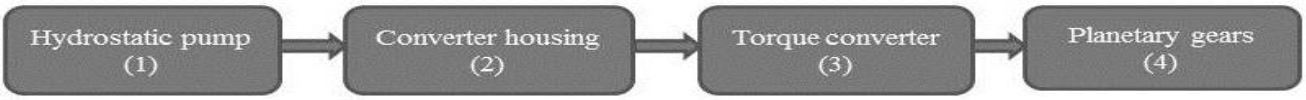


Figure 3. RBD of transmission for BD155.

4.1.2. Assumptions of Markov Modeling for BD155 Transmission

For modeling purposes, the following presumptions have been used:

i For all subsystems of the BD155 transmission, the rates of repair (μ) and failure (μ) are independent statistically and constant concerning time.

ii Mean time to repair (MTTR) and mean time to failure (MTTF) have exponential distributions.

iii Repairing damaged or repairable BD155 components should restore their original functionality. Worn-out parts are replaced with newer ones in the BD155.

iv There are no immediate subsystem breakdowns, and there is no likelihood that there will be one or more breakdowns and restorations in a specific amount of time. Due to the harsh operating and loading conditions, failures are frequent and make it challenging to locate all of the BD155 transmission's subsystems supported by housings or cases.

v There are two possible states for BD155 subsystems: operating and not functioning. When a system changes from a nonfunctioning state (downstate) to an operating condition (upstate), it indicates that the necessary repairs or replacements have been made. In contrast, when it changes from an operational state (upstate) to a nonfunctioning state (downstate), it designates that a subsystem has failed. The initial state does not impact how likely it is to move into the subsequent state [33].

4.1.3. Transition Diagram and Markov Modeling for BD155

According to Markov analysis, there are only two states in the transmission system. The letter "0" stands for the operational state, while the letters "i" (i = 1, 2, 3, 4) stand for the non-operational state. The machine starts initially in an operational state (i.e., at time t = 0), and the machine's subsystems can only return to a working condition after entering a non-operating state and vice versa, i.e., transitions only occur between the upstate and down. Subsystems, in this case, are continuous over time and exist in a discrete state. Here, the machine and its subsystems are in a state of communication. Various transition diagram-related equations have been created. These equations yield the machine's steady-state availability of various subsystems, and they also provide estimates of the machine's reliability for varying mission times [22,26,34]. Using the discussion mentioned above and transition diagram Figure 4, which is centered on RBD, the Markov modeling for dozer transmission in the BD155 can be established.

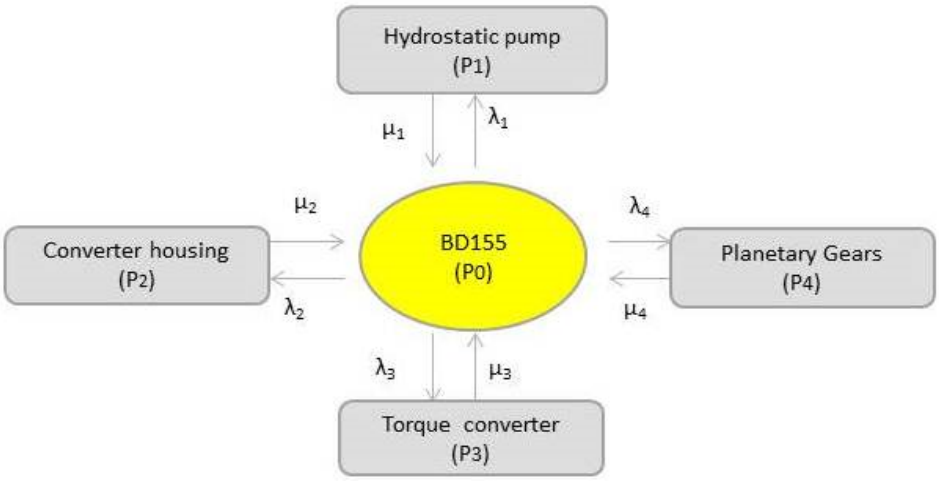


Figure 4. Transition diagram of BD155's subsystem.

Let $PS_0(t)$ stand for the probability that the BD155 transmission will be operational or "up" at time t. $PS_i(t)$ can be expressed as the likelihood of being in a "down" state for the duration of time "t," where i = 1, 2, 3, 4, and λ_i is the rate of failure of the transmission subsystem and μ_i is the rate of repair.

In operation, the following formulas can be used to express the probabilities of transmission at various time intervals (Δt) or at a later period (t + Δt):

$Ps_o(t + \Delta t)$ = [(*Probability of operational state at time t*) *and* (*probability that system won't deteriorate with time t* +Δ*t*)] +

[(*Failure probabilities at time t*) *and* (*Probability of being repaired at time t* +Δ*t*)] [31]

$$Ps_o(t + \Delta t) = [Ps_o(t)\ \{(1 - (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4)\ \Delta t\}] + [Ps_1(t)\mu_1\Delta t + Ps_2(t)\mu_2\Delta t + Ps_3(t)\mu_3\Delta t + Ps_4(t)\mu_4\Delta t]$$

$$Ps_o(t + \Delta t) - Ps_o(t) = -[(\lambda 1 + \lambda 2 + \lambda 3 + \lambda 4)\ \Delta t]\ Ps_o(t) + Ps_1(t)\mu_1\Delta t + Ps_2(t)\mu_2\Delta t + Ps_3(t)\mu_3\Delta t + Ps_4(t)\mu_4\Delta t$$

$$\frac{(Pso(t + \Delta t) - Pso(t))}{\Delta t} = -[(\lambda 1 + \lambda 2 + \lambda 3 + \lambda 4)]\ Pso(t) + Ps1(t)\mu 1 + Ps2(t)\mu 2 + Ps3(t)\mu 3 + Ps4(t)\mu 4$$

As $\Delta t \to 0$

$$\frac{dPso(t)}{dt} = \Sigma\ \mu i\ Psi\ (t) - Pso(t)\Sigma\ \lambda i \qquad where\ \ i = \ 1, 2, 3, 4 \tag{1}$$

Equating to 1st order derivative to zero for steady-state condition,

$$P_0\ (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4) = P_1\mu_1 + P_2\mu_2 + P_3\mu_3 + P_4\mu_4\ [i.e.,\ taking\ Ps_i\ (t) = P_i\ where\ i = 1, 2, 3, 4]$$

$$P_0\ \lambda_1 = P_1\mu_1$$
$$P_0\ \lambda_2 = P_2\mu_2$$
$$P_0\ \lambda_3 = P_3\mu_3$$
$$P_0\ \lambda_4 = P_4\mu_4 \quad (2)$$
$$P_0 + P_1 + P_2 + P_3 + P_4 = 1 \quad (3)$$

When the values P_0, P_1, P_2, P_3, and P_4 are substituted into Equation (3), the availability of BD155 transmission (steady-state) can be determined.

$$P_0 = \frac{1}{1 + \Sigma \frac{\lambda i}{\mu i}} \quad (4)$$

The steady-state availability of BD155 can be estimated using Table 2. and the above mentioned Markov equation and transition diagram (Figure 4).

Table 2. Failure and repair rates of BD155 transmission.

Operational Status	Rate of Failure λi/h	Rate of Repair μ_i/h	Working State Probability	Failed State Probability
Hydrostatic pump	0.060	1.512	P_0	P_1
Converter housing	0.190	0.619	P_0	P_2
Torque converter	0.312	1.193	P_0	P_3
Planetary gear	0.042	0.979	P_0	P_4

$$P_0 = \frac{1}{1 + \Sigma\ \frac{\lambda i}{\mu i}}\ 0.606\ where,\ \Sigma = 0.648$$

Hydrostatic pump unavailability, $P_1 = \frac{\lambda 1}{\mu 1} \times P_0 = 0.023$
Converter housing unavailability, $P_2 = \frac{\lambda 2}{\mu 2} \times P_0 = 0.185$
Torque converter unavailability, $P_3 = \frac{\lambda 3}{\mu 3} \times P_0 = 0.158$
Planetary gear unavailability, $P_4 = \frac{\lambda 4}{\mu 4} \times P_0 = 0.025$
The reliability of different subsystems of BD155 can be explained as,

$$R_1(t) = e^{-\lambda 1t},\ R_2(t) = e^{-\lambda 2t},\ R_3(t) = e^{-\lambda 3t},\ R_4(t) = e^{-\lambda 4t}$$

Since every subsystem in this transmission (BD155) is placed in series, therefore the product of each subsystem's performance determines the system's overall reliability.

$$R_{BD155}\ (t) = \Pi\ R_{i(t)} = e^{-\lambda 1t} \times e^{-\lambda 2t} \times e^{-\lambda 3t} \times e^{-\lambda 4t} = e^{(\sum - \lambda i)t}$$

Maintainability of the BD155′s subsystem can be found as

$$M_1(t) = 1 - e^{-\mu 1t},\ M_2(t) = 1 - e^{-\mu 2t},\ M_3(t) = 1 - e^{-\mu 3t},\ M_4(t) = 1 - e^{-\mu 4t}$$

Overall maintainability of BD155, $M_{BD155}\ (t) = \prod_{i=1}^{n}\ (1\ -\ e^{-(\mu i\ t)})$ where, n = no. of subsystem
Since the rate of failure of system is given as $\Sigma\lambda_i$, therefore $MTTF = \frac{1}{\Sigma \lambda i}$
and MTTR = MTTF $\times \sum_{i=1}^{n} \frac{\lambda i}{\mu i}$
Thus, availability, A(t) = $\frac{MTTF}{MTTF + MTTR}$.

5. Discussions on Analysis

Figures 5 and 6 provide graphical representations of R(t), and Table 3 provides reliability R(t) for the BD155 transmission and its subsystems. The subsystem's reliability R (t) decreases over time in Table 3 and Figures 5 and 6.

Table 3. Reliability R(t) of BD155′s subsystem.

Subassembly of BD155 Transmission					
Time (h)	**Hydrostatic Pump**	**Converter Housing**	**Torque Converter**	**Planetary Gear**	**Trans (BD155)**
0	1.0000	1.0000	1.0000	1.0000	1.0000
5	0.9378	0.8901	0.8798	0.8715	0.4977
10	0.8501	0.8251	0.7791	0.8254	0.3347
15	0.8005	0.7689	0.7517	0.7512	0.2281
20	0.7854	0.7091	0.6691	0.7114	0.1209
25	0.7323	0.6854	0.6413	0.6489	0.0972
30	0.6859	0.6351	0.5385	0.6207	0.0621
35	0.6431	0.5965	0.5071	0.5287	0.0279
40	0.5923	0.5484	0.4139	0.5189	0.0095
45	0.5355	0.4991	0.3485	0.4387	0.0021
50	0.4965	0.4684	0.3179	0.4062	0.0001
55	0.4219	0.4010	0.3005	0.3454	0.0001
60	0.4001	0.3785	0.2587	0.3312	0.0000
65	0.3979	0.3423	0.2317	0.2518	0.0000
70	0.3582	0.3001	0.2109	0.2117	0.0000
75	0.3030	0.2971	0.1894	0.1084	0.0000
80	0.2897	0.1413	0.0217	0.0521	0.0000
85	0.0959	0.0719	0.0189	0.0438	0.0000
90	0.0743	0.0585	0.0155	0.0312	0.0000
95	0.0197	0.0324	0.0073	0.0105	0.0000
100	0.0124	0.0011	0.0000	0.0001	0.0000

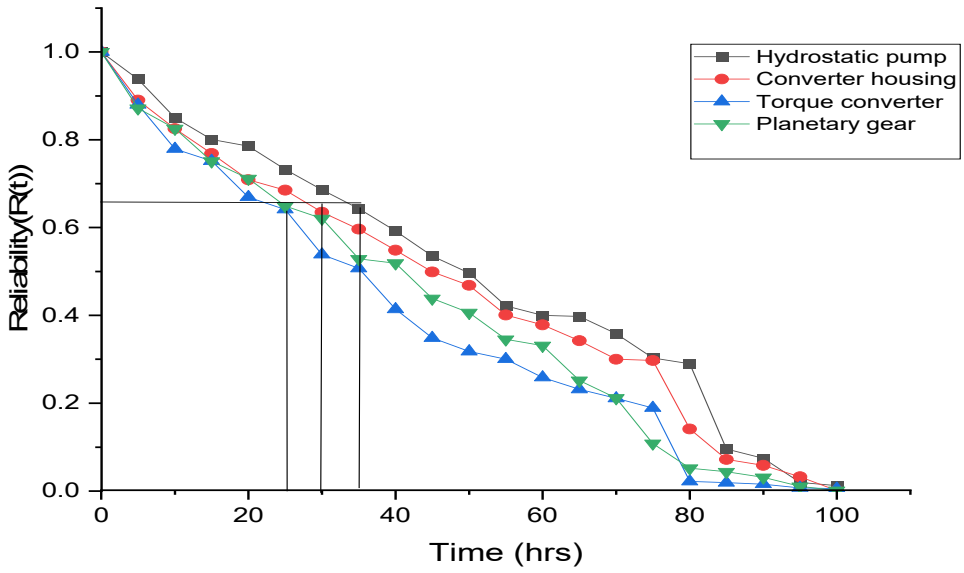


Figure 5. Reliability R(t) of BD155 transmission subsystem.

Compared to the others, the R (t) of the torque converter degrades more quickly (it reaches zero after 100 h). Since torque converters operate at very high rpm and have continuous duty cycles, the chances of excessive friction due to bad or worn bearings are quite predominant. The other main causes of failure are that heat buildup is likely to be

significant enough to require cooling. The operation of other subsystems is also hampered by failure-causing problems, such as oil leakages or an incorrect loading arrangement, overloading, using unrated lubricating oil, and employing the wrong bearing. From Figure 5, it can be observed that the torque converter loses almost 35% of reliability after 25 h of operation. Here Hydrostatic pump is most reliable (R (35) = 0.65) followed by converter housing (R (30) = 0.65) and planetary gear(R (25) = 0.65). All the subsystems are in series. Therefore, overall reliability will be a function of each subsystem, as shown in Figure 6. It is apparent that Rs(5) = 0.5 and Rs(10) = 0.33, which depicts that the reliability R(t) of BD155 has reduced.

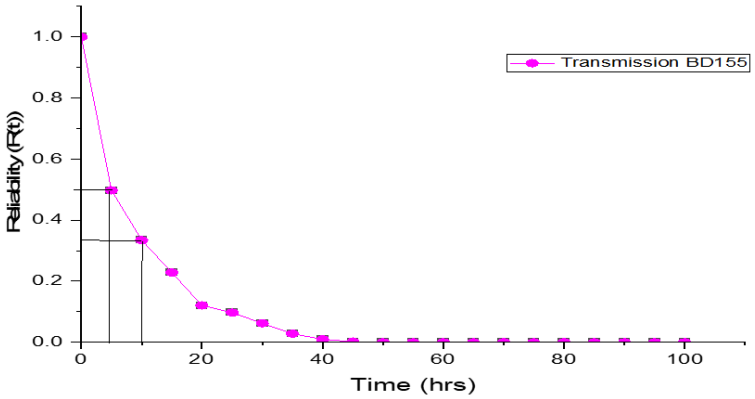


Figure 6. Reliability R(t) of BD155 transmission.

With the assistance of Table 4, Figures 7 and 8 can be used to examine maintainability M(t). The transmission and all of its supporting systems are increasing over time. During the initial phase of maintenance, the transmission and its supporting systems were turned off; they only resumed operation following repairs and replacements.

Table 4. Maintainability M(t) of BD155 subsystem.

Subassembly of BD155 Transmission					
Time (h)	**Hydrostatic Pump**	**Converter Housing**	**Torque Converter**	**Planetary Gear**	**Trans (BD155)**
0	0.0000	0.0000	0.0000	0.0000	0.0000
5	0.4592	0.5814	0.7857	0.6615	0.7715
10	0.5618	0.6886	0.8543	0.7714	0.8844
15	0.6697	0.7195	0.8954	0.8298	0.9169
20	0.7747	0.8091	0.9174	0.8819	0.9523
25	0.8798	0.8534	0.9367	0.9254	0.9758
30	0.8914	0.9157	0.9548	0.9999	0.9879
35	0.9729	0.9269	0.9699	0.9999	0.9989
40	0.9835	0.9387	0.9877	1.0000	0.9999
45	0.9944	0.9444	0.9934	1.0000	1.0000
50	0.9966	0.9584	0.9999	1.0000	1.0000
55	0.9975	0.9868	1.0000	1.0000	1.0000
60	0.9981	0.9999	1.0000	1.0000	1.0000
65	0.9999	1.0000	1.0000	1.0000	1.0000
70	1.0000	1.0000	1.0000	1.0000	1.0000
75	1.0000	1.0000	1.0000	1.0000	1.0000

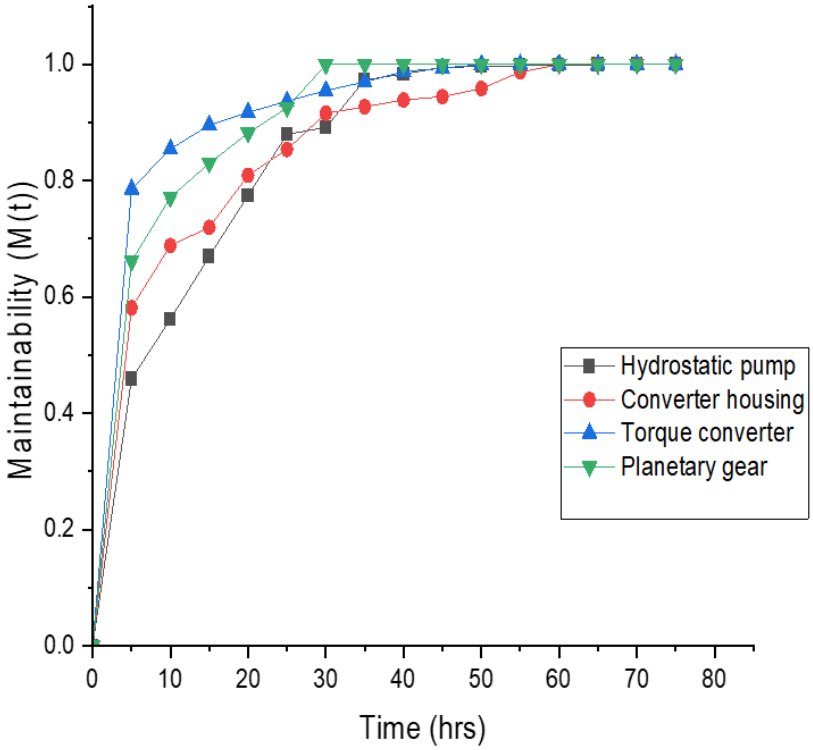


Figure 7. Maintainability M(t) of BD155 transmission subsystem.

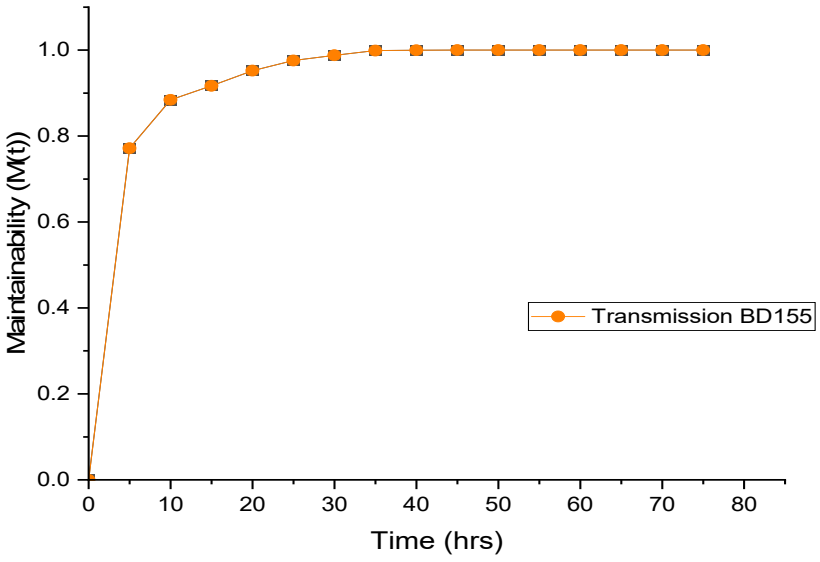


Figure 8. Maintainability M(t) of BD155 transmission.

Table 4 shows that planetary gears have better maintainability Ms(t) than other subsystems, as evidenced by the fact that they are ready for use after only 30 h of maintenance (Ms(30) = 0.999). In contrast, Figure 7 shows that converter housing requires the most time to regain early effectiveness (55 h). The absence of original spare parts is the leading cause of time-consuming maintainability. The transmission system returns to its initial condition or has the best probability of overcoming a failure condition after 35 h of maintenance policy. Figure 8 indicates that the system will regain its initial position after 35 h of maintenance.

The pie chart in Figure 9 displays that the availability A(t) of BD155 is approximately 62%, which appears to be relatively low compared to other A(t). Up to 38% of transmission subsystems are inoperable due to a lack of reliability and maintenance. The demanding settings in which the BD155 transmission operates require frequent corrective,

preventative, and productive maintenance. From Markov analysis, the unavailability of a hydrostatic pump, converter housing, torque converter, and planetary gear is 2%, 18%, 15%, and 3%, respectively.

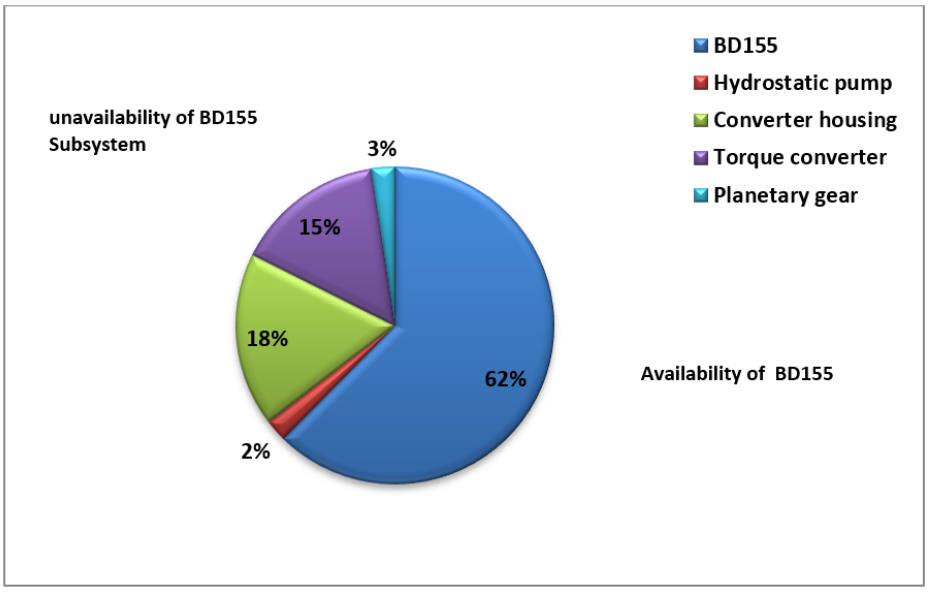


Figure 9. Availability A(t) of BD155 transmission and subsystems.

The total productive maintenance (TPM) methodology will increase reliability and reduce downtimes. The objective of using TPM is because it comprises all the maintenance policies such as predictive, corrective, and preventive maintenance, which will help to reduce BD155 transmission and its subsystem failures. Since preventive maintenance (PM) is TPM's main activity, the TPM PM analysis can also be performed. Defining the problem and magnitude in this methodology is the first step. It consists of ground investigation, equipment restoration, and analysis of past performances with the help of malfunction maps and PM maps. The malfunction map is a visual depiction of the tool that shows the location and kind of each failure discovered throughout the study, whereas PM maps are similar in principle but show failures in tool regions that are subject to routine maintenance [35].

Mathematically,

$$Rs_{PM}(t) = Rs(t) = 1 - F(t) = e^{-\lambda t},\ when\ 0 < t \leq T_{PM},\ Rs_{PM}(0) = Rs(0) = 0$$

$$Rs_{PM}(t) = R^n s\,(T_{PM})\ Rs\,(t - nT_{PM}),\ when\ nT_{PM} < t \leq (n+1)\,T_{PM},\ n \geq 1$$

Preventive maintenance (PM) with MTTF can be given as,

$$MTTFs_{PM}(t) = \int_0^{\alpha} Rs_{PM}(t)\,dt = [1 + \sum_{n=1}^{\alpha} R^n s\ T_{PM}] \int_0^{T_{PM}} R_s(t)dt = \int_0^{T_{PM}} R_s(t)dt / [1 - Rs\,(T_{PM})] = \int_0^{T_{PM}} (1 - F(t))dt / F(T_{PM})$$ [31]

Thus,

$$MTTFs_{PM}(t) = 1.5\ MTTF\ (t)$$

$$Availability_{PM} = \frac{MTTFpm}{MTTFpm + MTTR}$$

where, $Rs_{PM}(t)$ = System's reliability when preventive maintenance (PM)

$MTTF\ (t)$ = Mean time to failure without preventive maintenance (PM)

$MTTFs_{PM}(t)$ = Mean time to failure with preventive maintenance (PM)

$Availability_{PM}$ = Availability after preventive maintenance (PM)

The outcomes attained after implementing TPM PM strategies for the BD155 and its subsystems are as follows:

Before implementing the TPM PM methodology, the BD155 transmission and its sub-assemblies were not routinely inspected. Earlier in the implementation of TPM, inspections were only conducted when a problem manifested itself. Due to the prompt completion of corrective and preventative actions, availability increased. Failures can be anticipated, and it is sometimes necessary to take preventative action.

Hydrostatic pump: Pump and electric motor running noise should be monitored for any changes. Verify the oil levels in the power unit tanks and check the oil for temperature fluctuations. Tighten pipe clamps and screws if required.

Converter housing: The housing is thoroughly inspected for any physical damage brought on by vibration and shock because it serves as the TC's outer casing. Regular inspections and visual checks might help to avoid cracks. Regular checking of the oil level inside the casing reduces heat production.

Torque converter: Keeping the fluids' hydrostatic pressure constant is never easy. A regular inspection of the pump and stator helps to prevent high pressure. Changing transmission fluid periodically helps to reduce heat generation and prevents excessive friction within bearings.

Planetary gears: Thorough inspection of misaligned and worn-out gears is required as there is much wear and tear from continuous meshing. Repairs or replacements must be made as soon as feasible for worn-out or damaged components.

It was seen and assessed that there was a slight increase in reliability with decreased downtime and increased operational time after implementing the TPM PM methodology to BD155 subsystems. The statistical data gathered for the study should be accurate and trustworthy in order to obtain superior results. It was also found that the MTTF grew, but the MTTR stayed the same. From Figure 10, the availability of the BD155 has increased somewhat from 62% to 71%, while the unavailability of the hydrostatic pump, converter housing, torque converter, and planetary gears has decreased to 1%, 15%, 11%, and 2%, respectively.

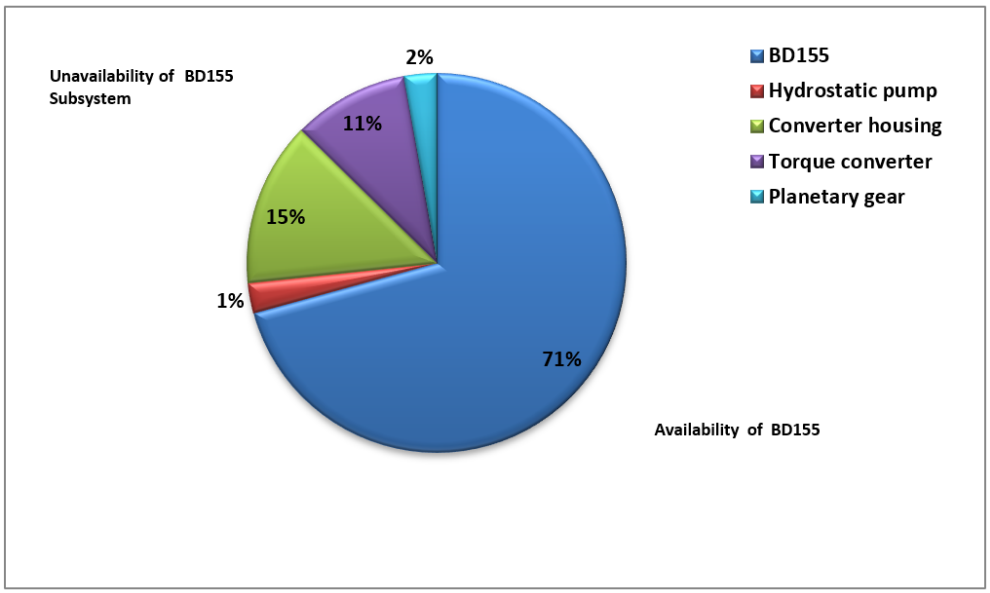


Figure 10. Reliability of BD155 transmission and subsystems after TPM PM.

In the existing literature survey, various authors have discussed the Markov method in a detailed manner to increase the reliability, availability, and maintainability of mining machinery, especially Agarwal and Samanta. Agarwal et al. investigated the RAM of tunnel boring machines and achieved the availability of EPBTBM up to 70% [26], whereas

Samanta et al. investigated reliability modeling on LHD and obtained up to 73% reliability [22]. Geeta et al. explored component-wise reliability to improve the microgrid's overall reliability and obtained 96% reliability [28]. Kumar et al. also carried out research based on Markov modeling in urea fertilizer plants and obtained optimum results [34]. The results are also comparable with the existing studies [36,37].

6. Conclusions

With the use of a transition diagram, Markov analysis has been addressed in this proposed research to establish R(t), M(t), and A(t) for the transmission of BD155 and its subsystems. The following are the main conclusions of the research that is being proposed:

i Due to its complicated operation, BD155 transmission faults are relatively frequent. All of the BD155's subsystems are interconnected in series, and their effects on R(t), M(t), and A(t) were studied to increase reliability. TPM policies and preventive maintenance (PM) techniques are used.

ii It is apparent that the reliability R(t) of the BD155 subsystem is deteriorating with time. Since each subsystem is coupled to the others in a series, overall reliability is a function of each subsystem. Additionally, Rs(5) = 0.5 and Rs(10) = 0.33 clearly show that R (t) of BD155 has decreased.

iii The transmission of the BD155's subsystems' maintainability M (t) is improving over time. In contrast, the converter housing needs the greatest time to regain early efficacy (55 h). Planetary gears have a superior maintainability Ms(t) than other subsystems and are ready for use after only 30 h of maintenance (Ms(30) = 0.999). The key factor contributing to the lengthy maintainability is the lack of original replacement parts. The result of 35 h of maintenance procedures is the transmission system's return to its original state.

iv Compared to others, BD155's availability A(t) is about 62%, which seems to be a low percentage. Due to poor reliability and maintenance, 38% of transmission subsystems are not functional. According to Markov analysis, there is a 2%, 18%, 15%, and 3% corresponding unavailability for the hydrostatic pump, converter housing, torque converter, and planetary gear.

v The total productive maintenance (TPM) approach has been used to boost reliability and decrease downtime. Considering that TPM's primary activity is preventive maintenance (PM), it is possible to undertake a TPM PM analysis as well. This process starts by identifying the issue and its scope. It entails ground research, equipment restoration, performance, and malfunction mapping for the study of previous performance.

vi Mathematical analyses have shown that the MTTRPM is 1.5 times the typical MTTF without changing the MTTR.

vii Additionally, the MTTF increased while the MTTR remained the same. The availability of the BD155 has increased from 62% to 71%, while the unavailability of the hydrostatic pump, converter housing, torque converter, and planetary gears has fallen to 1%, 15%, 11%, and 2%, respectively. This demonstrates the influence of TPM.

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