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SYSTEM RELIABILITY & NETWORK PERFORMANCE: RELIABILITY-CENTERED DESIGN (RCD) FOR PLASTIC PIPE INFRASTRUCTURE IN INDUSTRIAL ENGINEERING: OVERVIEW OF OPERATIONAL MANAGEMENT

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Abstract:

This research examines the failure and repair rates of machinery at a plastic pipe manufacturing facility, concentrating on extrusion lines, cooling systems, and cutting units. Data were gathered over a 12-month duration from a medium-sized factory manufacturing PVC and HDPE pipes. Metrics including Mean Time between Failures (MTBF) and Mean Time to Repair (MTTR) were examined to discern prevalent failure mechanisms and evaluate maintenance efficacy. The research indicated that extruders had the greatest failure rate, mostly attributable to screw degradation and heating element failures. The establishment of a systematic preventative maintenance program resulted in a 15% enhancement in equipment availability. These findings highlight the significance of maintenance planning in enhancing operational dependability and minimizing downtime.

Keywords: Laplace transform, Runge-Kutta fourth order differential equation, plastic pipe, utilized.

Introduction:

Reliability and maintenance have always been seen as essential elements of manufacturing efficiency. Moubray (1997) asserts that equipment dependability directly influences productivity, product quality, and operating expenses [1]. The implementation of Reliability-

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Centered Maintenance (RCM) in industrial environments has demonstrated efficacy in enhancing maintenance procedures and minimizing unanticipated downtime [2]. In plastic production settings, machinery like extruders and chillers undergo constant operation, rendering them especially susceptible to mechanical and thermal wear [3]. Frequent failures in plastic processing lines are commonly ascribed to poor lubrication techniques, component misalignment, and insufficient preventative maintenance scheduling. Plastic processing machinery has consistent failure patterns. Al-Taie and Ismail [4], examined extrusion-based PVC pipe manufacturing systems and identified prevalent failures, including malfunctions of temperature control units, die obstructions, and motor breakdowns. Choudhury and Dey [5], investigated extruder screw wear, determining that abrasive additive such as calcium carbonate markedly decreased operating lifespan and heightened maintenance frequency. Cooling equipment and cutters encounter reliability issues. Singh and Agnihotri [6], documented recurrent corrosion in cooling tanks and mechanical failures in pipe cutters attributed to misalignment and vibration, indicating the necessity for improved design and maintenance protocols. When assessing the efficacy of a maintenance program, important measures such as MTBF and MTTR are frequently used. These were defined by Mobley [7], as essential metrics for tracking equipment status and organizing repair tasks. Through the use of systematic scheduling and operator training, Raut et al. [8], increased Overall Equipment Effectiveness (OEE) by 20% after implementing Total Productive Maintenance (TPM) at a plastic molding facility. Notwithstanding these advancements, few research explicitly examines maintenance efficacy in plastic pipe production, resulting in a deficiency of sector-specific standards and procedures.

Revolutionizing predictive maintenance is the merging of data analytics with the Internet of Things. By analyzing vibration and heat data in real-time, Raza et al. [9], demonstrated that equipment breakdowns may be predicted with high accuracy, leading to a 25% reduction in unexpected downtime. Cost and a lack of technical knowledge prevent these instruments from being widely used in small and medium plastic pipe factories, even though they are more prevalent in large-scale or high-tech facilities.

The dependability of a system is a critical factor in assessing the performance of an engineering system. As a system's complexity escalates, its dependability diminishes unless appropriate preventive measures are included. High reliability can be attained by the provision of adequate redundant components or by augmenting the system's capacity. To conserve time and costs, one can permit many suboptimal repairs prior to replacing the system with a new one or achieving a flawless repair. To evaluate the dependability of a system, we presume it is under constant surveillance. Upon system failure, repair work commences, and once finished, the system is restarted for functioning. The objective is to restore the malfunctioning system to operational status promptly. While substituting with a new unit is the most expedient approach, it is not always preferable due to its high cost. Consequently, the reutilization of the repaired unit is nearly obligatory. Consequently, we must examine the system's dependability and accessibility within certain parameters. Various scholars have examined these concerns in their research articles with diverse methodologies. Upon deriving the differential equations that regulate of an arrangement by utilizing the transformation diagram's commemoration rule of

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thumb, several mathematical methods were employed to solve these equations in order to determine dependability.

The most crucial piece of manufacturing equipment in the plastics sector, extruder lines are the biggest converters of polymers on a global scale. Extrusion lines are designed to provide benefits in terms of operational cost (output per hour) from a business perspective. Motion pictures, spreadsheets, characteristics, blasted shapes, coverings, threads, plumbing, containers, cables, etc. countless more may be made using extrusion. Extrusion produces a variety of useful products, but among the most essential are pipes, which find widespread use in many different sectors. Their nearly infinite versatility and their ability to produce indefinitely in response to changing market demands are two of the keys selling points for processors and markets [10]. The manufacturing of thermoplastic pipe systems is a substantial business that is responsible for a considerable number of polymers coming into circulation. The construction sector is the second largest market for polymers in the world, and it contributes significantly to the use of plastics materials. With regard to the manufacture of pipes, this amounts to the entire marketplace demand of roughly three Europe's billions of pounds over the 2000s period [11]. Commercial manufacture of plastic pipes commenced in the late 1930s. Various meanings are typically linked to distinct businesses such as plumbing, gas transportation, drinks, medicine, and mining. The most recognized and accepted definition is that a pipe is a stiff, hollow, elongated structure with a diameter bigger than that of tubes [10]. Tubing's are fundamentally similar, differing mostly in their flexibility, reduced diameter, and thin walls, which may measure up to 6 inches in diameter [12].PVC for plastic pipe is among the most lucrative products in the chemical business for income generation. Worldwide, more than 50% of produced PVC (for plastic pipe) is utilized in building. PVC (plastic pipe) is an economical and easily assembled construction material. In recent years, PVC (plastic pipe) has supplanted conventional construction supplies including ceramics, mortar, and lumber in several applications. Notwithstanding assertions that PVC (plastic pipe) manufacture adversely impacts Health for people and our surroundings, it is extensively utilized [13]. PVC for plastic pipe has several applications. As a stiff polymer, it is utilized in vinyl siding, magnetic stripe cards, window profiles, pipes, and plumbing and conduit fittings. PVC for plastic pipe is frequently utilized as insulation for electrical cables. In situations PVC for polyethylene pipe-free LSOH (low-smoke, zero-halogen) insulation of cables is used in areas wherein smoke poses a serious problem, especially in underground commonly utilized [14].

Polyvinyl chloride is frequently extended in flat sheet form to produce voids in the material, adding thickness without adding weight. Numerous commercial signage products are made using these sheets and films. In the building business, plasticized polyvinyl chloride (PVC for plastic pipe), sometimes referred to as vinyl in the USA and the UK, and is utilized as a low-maintenance material. Waste pipes, drainpipes, gutters, and down pipes are all made of the same material, which has virtually completely replaced cast iron in plumbing and drainage [14]. Recycling of polyvinyl chloride (PVC for plastic pipe) can be accomplished in a variety of methods. There are several producers of PVC for plastic pipe that have programs to recycle vinyl, recycling both waste from the production process back into their goods and post-consumer PVC for plastic pipe building materials in order to lessen the amount of garbage that

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is sent to landfills. The selection of a particular material for use in pipes is constrained by the requirements for performance, installation, and maintenance, in addition to the components that are readily available for use in fittings. The majority of thermoplastics may be utilized for applications that call for maximal joint strength and chemical resistance; however, an initial bonding step is required for these thermoplastics to be utilized [10]. PVC for plastic pipe is the material that is most often used in molding. When it comes to PVC dry mixes, the maker can use their own compounding formulas, which should save them money [15]. In the substance is commonly used in thermoplastic pressurizer's pipe structures for wastewater and sewage pipes due to its cost-effectiveness and flexibility. PVC for plastic pipe i.e. plumbing pipes is often white, although ABS pipes are frequently found in both grey and white [16]. Pipes made of polyvinyl chloride are common. In the United States, it makes up 66% of the water distribution market and 75% of the sanitary sewer pipe applications. Residential water supply piping systems can now make use of chlorinated polyvinyl chloride (CPVC) pipe, according to a modification to the California Building Standards Code in February 2007. Although CPVC has gained widespread acceptance in the United States since its introduction in 1982, the state of California has only allowed restricted usage of the material since 2001. An Environmental Impact Report was created and verified by the Department of Housing and Community Development. The report suggested that the Commission accept and adopt the usage of CPVC. With a unanimous decision, the Commission included CPVC in the California Plumbing Code of 2007 [17].

Remark: Moubray's Reliability-Centered Maintenance (RCM) (1997) and Raza et al.'s Predictive Maintenance Utilising IoT (2020) exhibit substantial differences in their methodologies, technologies, and applications. Moubray's RCM is a systematic, analytical approach that emphasises determining the optimal maintenance strategy—be it preventative, predictive, or run-to-failure—grounded on failure modes, functional analysis, and risk evaluation. It mostly depends on expert assessment and previous failure data instead of real-time surveillance, rendering it a more conventional but essential methodology relevant across sectors such as aviation, energy, and heavy manufacturing. Conversely, the research of Raza et al. exemplifies a contemporary, data-centric advancement in maintenance, using IoT sensors, machine learning, and cloud computing to provide real-time predictive maintenance (PdM). Their methodology is extensively automated, enabling real-time modifications in maintenance plans according to current equipment conditions, and is especially appropriate for smart factories and Industry 4.0 contexts, including the plastic processing sector. Moubray's RCM offers a strategic framework for maintenance decision-making, while Raza et al.'s IoT-based PdM illustrates how digital transformation improves prediction accuracy and operational efficiency. Collectively, these works demonstrate the transition from manual, experience-dependent maintenance to intelligent, data-driven systems.

Recent studies in plastic pipe reliability engineering have advanced significantly in comprehending failure processes, formulating prediction models, and assessing performance under harsh situations. Frank et al. (see[18]) identified slow crack growth (SCG) as a primary failure mode in high-density polyethylene (HDPE) pipes, especially in gas distribution systems, whereas Janson and Kurihara (see[19]) illustrated how environmental stress cracking

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(ESC) exacerbates degradation in chlorinated water environments. Zhou et al.(see[20]), formulated sophisticated accelerated ageing methods integrated with probabilistic modelling, resulting in enhanced accuracy in lifespan forecasts for polyethylene pipes.

Emerging technologies have improved dependability evaluations, as shown by Wang et al.[21],, who used machine learning techniques to analyse acoustic emission data for the early identification of leaks in municipal water systems. Comparative analyses of material performance under extreme conditions have provided significant insights: Kim and Zhang [22], discovered that cross-linked polyethylene (PEX) pipes demonstrate diminished longevity in geothermal applications surpassing 60°C, whereas research by the National Institute of Standards and Technology (NIST, 2023)[23], validated HDPE's enhanced performance in seismic regions owing to its intrinsic flexibility.

The domain has also seen progress in standardisation and risk assessment approaches. The International Organisation for Standardisation (ISO, 2021)[24], revised its testing methodologies (ISO 9080) for pressure pipe systems, while Santos et al. (2023) used Bayesian network modelling to assess failure probability in urban water infrastructure. Nonetheless, persistent obstacles exist, especially concerning the dependability of recycled materials (Environmental Protection Agency [EPA], 2024)[25], and the practical use of smart pipe technology (Lee et al.[26]). These works jointly emphasise the crucial convergence of materials science, predictive analytics, and infrastructure monitoring in enhancing the dependability of plastic pipes.

Plastic pipes are become an integral part of our daily lives. These serve several purposes, including the conveyance of potable water as well as other liquids and gasses. Compared to iron pipes, plastic pipes are stronger and endure far longer. Wet and humid environments accelerate iron corrosion, shorten its lifespan, weaken it, and make it more susceptible to leaks and other problems. By bending it using heat or chemicals, a plastic pipe can become an insoluble or almost insoluble substance. Whether made of natural or synthetic binders or resins and with or without molding chemicals, plastic pipes are an organic product. Plastic pipes, in the broadest sense, are carbon-containing materials that also include hydrogen, nitrogen, and oxygen. Carbon generates increasingly complex molecules when it mixes with other elements.

An extrusion process manufactures plastic pipes, which may be described as the forcing of a substance through a die opening. This die orifice shapes the final product. An engineering elucidation of plastic pipe extrusion might resemble a product description. A technical description of plastic pipe extrusion entails the heating and melting of plastic resin grains, followed by their mixing and shaping into pipe shape. Various chemicals are utilized in distinct proportions for the fabrication of plastic pipe. Plastic is an organic material. The completed plastic product is inflexible and stable at ambient temperature. It is crucial to pick the most appropriate plastic material for each application, particularly for the fabrication of plastic pipes. Figure 1 provides a concise overview of a plastic production facility.

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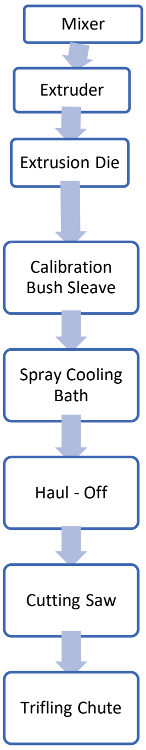
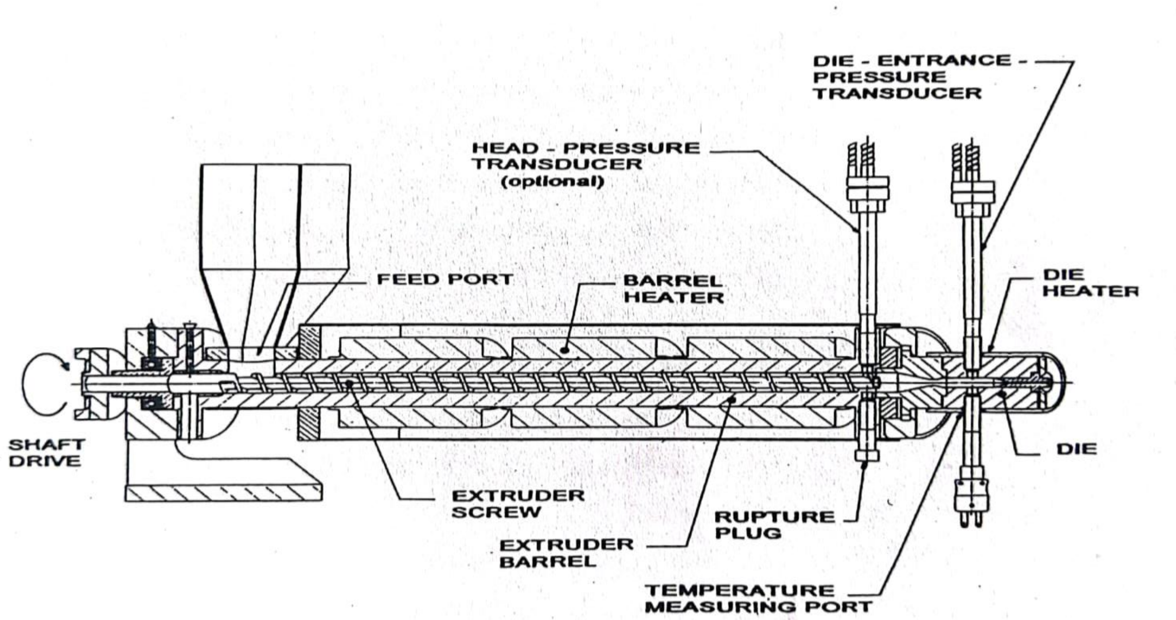


Caption: figure 1: *production process flow diagram for plastic pipes*



Caption: figure 2: extruder diagram

SYMBOLS AND RELIGION SYSTEM

There are eighteen components in the factory that produces plastic pipes.

1. Mixer (S_1): It combines raw ingredients in the right proportions for pipe producing goods, including oil, magnesium carbonate, and other compounds. It has an appliance that brings the

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raw material's temperatures up to 140° C. After cooling to 100° C, the hot product is sent to the twister. The only possible outcome for this component is a complete breakdown.

2. An extruder (S_2): In this phase, the unprocessed product in the blender is heated. To bring up the raw material's temperatures to various degrees, it has eight burners. The nutritional value of the good is dependent on the way it is heated. The component is not affected whenever one or two warmers fail; whenever when a number of radiators malfunction, the network as a whole malfunctions. This part is especially prone to serious malfunctions.

3. Retractable Die (S_3): It is used to create pipelines of various sizes. There is an automatic backup mechanism. As a result, one could argue that it is always successful.

4. Adjustment Slipcover for the Bush (S_4): Reducing the heat in pipelines that previously were treated is its goal. Because of its reserve component, it is always guaranteed to function.

5. N taps are set to run simultaneously in sub-system S_5 (Spray Conditioning Bathtub) to cool the conduit. Only in the event that K out of N taps breakdown does it fail.

6. Haul-Off (S_6): Due to the units' series arrangement, this three-unit arrangement is only vulnerable to a complete breakdown. The piping is taken out of the chilling solution and moved to the chopping saw by means of this component.

7. Reducing Saw (S_7): Although each of the components are arranged in succession, this three-unit arrangement is only vulnerable to a total breakdown. The piping is taken out of the chilling bath and moved to the chopping saw by means of this component.

8. Superficial Funnel (S_8): It is in charge of network aggregation and is additionally utilized to gauge network lengths. According to agricultural technologists, that component is thought to be foolproof.

The findings: –

Furthermore, we have added the following symbols in along with the ones used for exceptional situations of components, including S_1, S_2, S_3, S_4, S_5, S_6, S_7, and S_8:

1. The values λ_1, λ_2, λ_3, and λ_4 represent the ongoing breakdown rate for components S_1, S_2, S_3, and S4, correspondingly.

r represents the subsystem's constant malfunction probability. S_5.

Show the components of subsystems S_1, S_2, S_3, and S_4's individual set upkeep rates.

Indicate a set sub-system upkeep expenseS_5.

f_m (t): likelihood that the system will operate is in m^{th} state at time t, m=1,2,3,…,11.

Small letters x_1, x_2, x_5, x_6, and x_7 show the corresponding sub-system's failure statuses S_1, S_2, S_5, S_6, and S_7.

Assumptions:

The breakdown and replacement percentages are presented in increments of a single day and are unrelated to their relationship.

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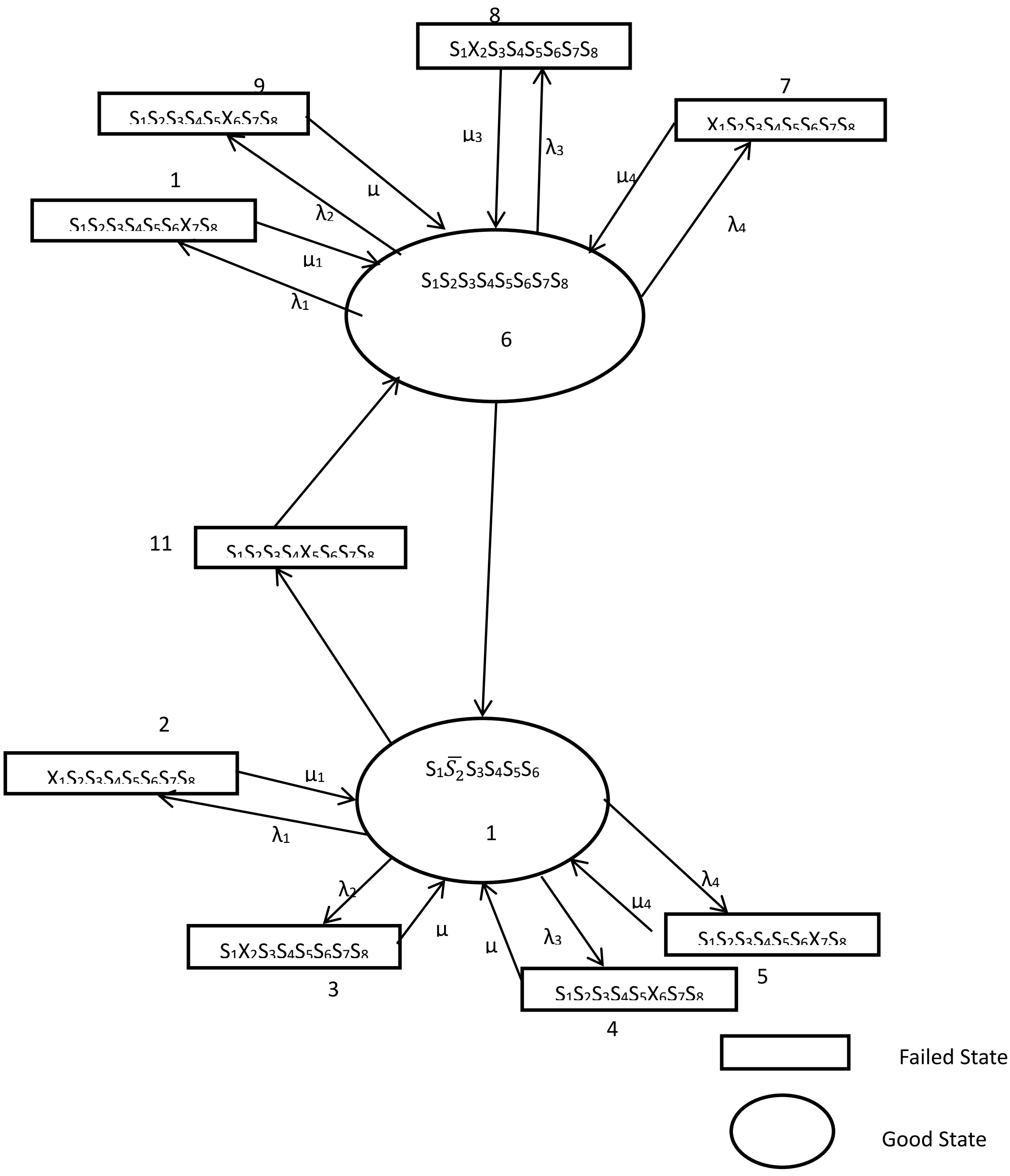
No multiple subsystems are experiencing simultaneous failures.

3. Components S_3, S_4, and S_8 are foolproof because the conversion equipment utilized for reserve components are perfect.

4. Sub-system S_5 is doomed if J = 10 and V = 2 knocks are unsuccessful.

S_1 what was repaired is the same as a brand-new one.



Caption: figure 3: transition diagram of the whole system

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Using the previously given annotations and suppositions figure (3) shows the transitional diagrams for all of the systems.

It can be explained mathematically in the following way:
Short-term Circumstance: The following set of first-order linear equations pertaining to the system's temporal diagrams is obtained by likelihood assessment.

$\frac{df_1(t)}{dt}$ + (r + λ_1 + λ_2 + λ_3 + λ_r) $f_1(t)$ = $\rho f_{11}(t)$ + $\mu_1 f_2(t)$ + $\mu_2 f_3(t)$ + $\mu_3 f_4(t)$ + $\mu_4 f_5(t)$ … (1)

$\frac{df_2(t)}{dt}$ + $\mu_1 f_2(t)$ = $\lambda_1 f_1(t)$… (2)

$\frac{df_3(t)}{dt}$ + $\mu_2 f_3(t)$ = $\lambda_2 f_1(t)$… (3)

$\frac{df_4(t)}{dt}$ + $\mu_3 f_4(t)$ = $\lambda_3 f_1(t)$… (4)

$\frac{df_5(t)}{dt}$ + $\mu_4 f_5(t)$ = $\lambda_4 f_1(t)$… (5)

$\frac{df_6(t)}{dt}$ + (r + λ_1 + λ_2 + λ_3 + λ_4) $f_6(t)$ = $rf_1(t)$ + $\mu_1 f_7(t)$ + $\mu_2 f_8(t)$ + $\mu_3 f_9(t)$ + $\mu_4 f_{10}(t)$… (6)

$\frac{df_7(t)}{dt}$ + $\mu_1 f_7(t)$ = $\lambda_1 f_6(t)$… (7)

$\frac{df_8(t)}{dt}$ + $\mu_2 f_8(t)$ = $\lambda_2 f_6(t)$… (8)

$\frac{df_9(t)}{dt}$ + $\mu_3 f_9(t)$ = $\lambda_3 f_6(t)$… (9)

$\frac{df_{10}(t)}{dt}$ + $\mu_4 f_{10}(t)$ = $\lambda_4 f_6(t)$… (10)

$\frac{df_{11}(t)}{dt}$ + $\rho f_{11}(t)$ = $rf_6(t)$… (11)

The boundary conditions are

$f_m(0) = 1$ for m = 1

$f_m(0) = 0$ for $m \neq 1$… (12)

The aforementioned system of equations may be expressed as

($\emptyset$I – X) $f_v(t)$ = 0 … (13)

where $\emptyset = \frac{d}{dt}$, is the differential operator , I is an 11-identity and 0 is an 11-null matrix,

$f_v(t) = [f_1(t), f_2(t), f_3(t), \dots, f_{11}(t)]^T$,

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$$X=\begin{bmatrix}
-(r+\lambda_1+\lambda_2+\lambda_3+\lambda_4) & \mu_1 & \mu_2 & \mu_3 & \mu_4 & 0 & 0 & 0 & 0 & 0 & 0\\
\lambda_1 & -\mu_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
\lambda_2 & 0 & -\mu_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
\lambda_3 & 0 & 0 & -\mu_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0\\
\lambda_4 & 0 & 0 & 0 & -\mu_4 & 0 & 0 & 0 & 0 & 0 & 0\\
r & 0 & 0 & 0 & 0 & -(r+\lambda_1+\lambda_2+\lambda_3+\lambda_r) & 0 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & \lambda_1 & -\mu_1 & 0 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & \lambda_2 & 0 & -\mu_2 & 0 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & \lambda_3 & 0 & 0 & -\mu_3 & 0 & 0\\
0 & 0 & 0 & 0 & 0 & \lambda_4 & 0 & 0 & 0 & -\mu_4 & 0\\
0 & 0 & 0 & 0 & 0 & r & 0 & 0 & 0 & 0 & 0
\end{bmatrix}$$

Let Z be the transformation matrix X, such that

$Z^{-1}XZ = Y$… (14)

where $F = diag(u_1,u_2,\ldots,u_{11})$: $u_1,u_2,\ldots,u_{11}$ being the eigen values of X.

Currently, pre-multiplying (13) by Z^{-1} and using (14), we get

$(\phi I - F)H_v(t) = 0$… (15)

where $H_v(t) = Z^{-1}f_v(t)$… (16)

In the event that we are able to calculate $H_v(t) = Z^{-1}f_k(t)$, then $f_v(t)$ may be ascertained by the transformation,

$f_v(t)=ZH_v(t)$… (17)

Equation (15) is a linear matrix differential equation in $H_v(t) = Z^{-1}f_v(t)$, whose solution is given by

$H_v(t) = \exp(Ft)\varphi$ … (18)

Where $\varphi = A_v(0) = Z^{-1}f_v(0)$… (19)

and $f_x(0)$ is a column vector, all of whose elements are 0 except the first element, which is 1.

Hence, we get

$fv(t) = Z \exp(Ft)Z^{-1}fv(0)$… (20)

Consequently, all probabilities may be derived as polynomials in t, which will subsequently provide the system's dependability for a specified value of t. The system of differential equations (1) to (11), accompanied by the specified boundary conditions (12), has been resolved using,

The technique and the system's dependability have been calculated over the time interval from t = 0 to t = 360 days, considering various repair and failure rates of the sub-systems. The dependability R(t) of the system may be calculated as

$R(t) = f_1 + f_6$… (21)

Equilibrium Condition:

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In process industries, management often prioritizes the long-term availability of the system. The steady-state probability of the systems are derived by calculating $\frac{d}{dt} \to 0$, as t $\to \infty$.

Equations (i) and (ii) are reduced to the following in this limited case.

Here, we have made advantage of f_m for $f_m(t\to \infty)$, m=1,2,…,11 for indicating probabilities that are in a stable condition.

Now $(r + \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4) f_1 = \mu_1 f_2 + \mu_2 f_3 + \mu_3 f_4 + \mu_4 f_5 + \rho f_{11}$ … (22)

$\mu_1 f_2 = \lambda_1 f_1$ … (23)

$\mu_2 f_3 = \lambda_2 f_2$ … (24)

$\mu_3 f_4 = \lambda_3 f_3$ … (25)

$\mu_4 f_5 = \lambda_4 f_4$ … (26)

$(r + \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4) f_6 = \mu_1 f_7 + \mu_2 f_8 + \mu_3 f_9 + \mu_4 f_{10} + r f_1$ … (27)

$\mu_1 f_7 = \lambda_1 f_6$ … (28)

$\mu_2 f_8 = \lambda_2 f_6$ … (29)

$\mu_3 f_9 = \lambda_3 f_6$ … (30)

$\mu_4 f_{10} = \lambda_4 f_6$ … (31)

and $\rho f_{11} = r f_6$ … (32)

By solving these equations recursively, we get

$f_2 = \frac{\lambda_1}{\mu_1} f_1$ … (33)

$f_3 = \frac{\lambda_2}{\mu_2} f_1$ … (34)

$f_4 = \frac{\lambda_3}{\mu_3} f_1$ … (35)

$f_5 = \frac{\lambda_4}{\mu_4} f_1$ … (36)

$f_7 = \frac{\lambda_1}{\mu_1} f_6$ … (37)

$f_8 = \frac{\lambda_2}{\mu_2} f_6$ … (38)

$f_9 = \frac{\lambda_3}{\mu_3} f_6$ … (39)

$f_{10} = \frac{\lambda_4}{\mu_4} f_6$ … (40)

$f_{11} = \frac{r}{\rho} f_6$ … (41)

Now, normalizing condition $f_1 + f_2 + f_3 + f_4 + f_5 + f_6 + f_7 + f_8 + f_9 + f_{10} + f_{11} = 1$… (42), we get

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$f_1 = \frac{1}{2}\left[1 + \frac{\lambda_1}{\mu_1} + \frac{\lambda_2}{\mu_2} + \frac{\lambda_3}{\mu_3} + \frac{\lambda_4}{\mu_4} + \frac{r}{2\rho}\right]^{-1}$ … (43)

It is now possible to ascertain the availability in the long run as

$A(\infty) = f_1 + f_6$ … (44)

$= \left[1 + \frac{\lambda_1}{\mu_1} + \frac{\lambda_2}{\mu_2} + \frac{\lambda_3}{\mu_3} + \frac{\lambda_4}{\mu_4} + \frac{r}{2\rho}\right]$… (45)

A study of behavior

A STATE OF TRANSIENCE

The equipment's durability has been determined using a range of maintenance and disintegration rate combos, as shown in formula (4.13). It is crucial to recognize that the permutations listed previously are not all-inclusive and that we have just assessed the most crucial elements of the calculation. A range of variations in failures and maintenance rates create the system's trustworthiness, that is calculated and presented in Tables 1 through 2. The mean duration between breakdown (MTBF) in months, particularly reflects the various percentages of failures, is shown in the last paragraph of the information displayed. The MTBF was calculated using Simpson's one-third criterion.

1. How reliable the system is affected by the mixing system breakdown rate (λ_1) 1. How system reliability is affected by the mixing device breakdown rate (λ_1)

The factors that follow were used to measure the system's reliability: λ_1 = 0.0025, 0.0027, 0.0029, 0.0030; λ_2 = 0.0005; λ_3 = 0.0009; λ_4 = 0.0011; γ = 0.0054; μ_1 = 4.800; μ_2 = 0.033; μ_3 = 0.0999; μ_4 = 0.0015; 0.4999; and δ = 12.000. Table 4.1 presents the findings of this investigation.(a). According to the data, when the breakdown rate increases from 0.0025 to 0.0030, efficiency and MTBF drop by about 0.01%. As the time increases from 30 to 360 days, trustworthiness decreases by approximately 0.6%.

Table 1

λ_1 → DAYS↓	**0.0025**	**0.0027**	**0.0029**	**0.0030**
30	0.979490	0.979450	0.979410	0.979390
60	0.975678	0.975639	0.975599	0.975579
90	0.974400	0.974361	0.974321	0.974301
120	0.973927	0.973888	0.973849	0.973829
150	0.973748	0.973708	0.973668	0.973648
180	0.973675	0.973636	0.973596	0.973576
210	0.973644	0.973605	0.973566	0.973546
240	0.973630	0.973590	0.973551	0.973531

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270	0.973623	0.973583	0.973544	0.973524
300	0.973618	0.973579	0.973539	0.973519
330	0.973615	0.973576	0.973537	0.973517
360	0.973613	0.973574	0.973534	0.973515
MTBF	351.0875	351.0737	351.0599	351.0529

Caption: table 1: impact of mixer failure rate on system dependability

(ii) Impact of the lamination disintegration rate (λ2) on the framework's dependability

By adjusting the extruder's breakdown rate, we have investigated how the subsystem's rate of breakdown affects the system's ultimate trustworthiness. λ_2 to 0.0003, 0.0005, 0.0007, and 0.0009. The following are the alternate breakdown and maintenance prices: λ_1 = 0.0027, λ_3 = 0.0009, λ_4 = 0.001, and γ = 0.0054. μ_1 = 4.800, μ_2 = 0.033, μ_3 = 0.0999, μ_4 = 0.0015, 0.4999, and δ = 12.000. Utilizing such information, the reliability of the framework is assessed; the results are displayed in Table 4.1(b). This table shows the fact that as the breakdown rate increases from 0.0003 to 0.0009, the system's reliability and MTBF decrease by about 1.5%. Nevertheless, trustworthiness drops from 0.39% to 1.02% as the duration extends from 30 to 360 days.

Table 2

λ_2→ DAYS↓	**0.0003**	**0.0005**	**0.0007**	**0.0009**
30	0.983150	0.979450	0.975768	0.972104
60	0.980665	0.975639	0.975654	0.965709
90	0.979867	0.974361	0.968909	0.963512
120	0.979568	0.973888	0.968270	0.962713
150	0.979450	0.973708	0.968030	0.962416
180	0.979401	0.973636	0.967937	0.962303
210	0.979379	0.973605	0.967898	0.962258
240	0.979368	0.973590	0.967881	0.962238
270	0.979361	0.973583	0.967873	0.962229
300	0.979357	0.973579	0.967868	0.962224
330	0.979354	0.973576	0.967865	0.962221
360	0.979352	0.973574	0.967863	0.962219
MTBF	**352.9831**	**351.0737**	**349.1849**	**347.3155**

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Caption: table 2: impact of extruder failure rate on system dependability

(iii) Impact of the spray-cooled solution failure probability (γ) on system dependability

Using four coolant spray solution breakdown stages, ranging i.e., γ=0.0050, 0.0052, 0.0054, and 0.0056, together with other variables such λ_1= 0.0027, λ_2=0.00052, λ_3=0.0009, λ_4=0.0011, μ_1= 4.800, μ_2=0.033, μ_3=0.0999, μ_4=0.4999 and =12.000, We have now calculated the system's dependability. Table 1 is a tabulation of this dependability. According to the table, the accuracy drops by roughly 0.6% as the duration increases from 30 to 360 days. As the failed component rate rises from 0.0050 to 0.0056, the MTBF falls and the dependability drops from 0.0012% to 0.0026%.

Table 3

μ_1→ DAYS↓	**0.0050**	**0.0052**	**0.0054**	**0.0056**
30	0.979458	0.979454	0.979450	0.979446
60	0.975651	0.975645	0.975639	0.975632
90	0.974376	0.974368	0.974361	0.974353
120	0.973905	0.973897	0.973888	0.973880
150	0.973725	0.973716	0.973708	0.973699
180	0.973653	0.973645	0.973636	0.973627
210	0.973623	0.973614	0.973605	0.973596
240	0.973608	0.973600	0.973590	0.973582
270	0.973601	0.973592	0.973583	0.973574
300	0.973596	0.973587	0.973579	0.973570
330	0.973593	0.973584	0.973576	0.973567
360	0.973591	0.973582	0.973574	0.973566
MTBF	**351.0792**	**351.0764**	**351.0737**	**351.0709**

Caption: table 3: Impact of spray cooling bath failure rate on system dependability

iv) Effect of system availability on mixing maintenance rate (μ_1)

The effect of the sub-system mixer's replacement rate on its reliability has now been examined utilizing its four phases: μ_1=4.600,5.000, and5.200. Considering the other breakdown and replacement frequencies are as follows, we obtain λ_1 = 0.0027, λ_2 = 0.0005, λ_3 = 0.0009, λ_4 = 0.0011, γ = 0.0054, μ_2 = 0.033, μ_3 = 0.0999, μ_4 = 0.4999, and δ = 12,000, accordingly. Table 4 displays the outcome of a calculation made using this data to ascertain the system's reliability. According to the statistics in this table, increasing the replacement rate from 4.600 to 5.200

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results in an approximate 0.007% improvement in the product's dependability and MTBF. However, when the time period is extended from 30 to 360 days, the product's overall trustworthiness decreases by only 0.6%.

Table 4

μ_2→ DAYS↓	**4.6**	**4.8**	**5.0**	**5.2**
30	0.979490	0.979450	0.979410	0.979390
60	0.975678	0.975639	0.975599	0.975579
90	0.974400	0.974361	0.974321	0.974301
120	0.973927	0.973888	0.973849	0.973829
150	0.973748	0.973708	0.973668	0.973648
180	0.973675	0.973636	0.973596	0.973576
210	0.973644	0.973605	0.973566	0.973546
240	0.973630	0.973690	0.973551	0.973531
270	0.973623	0.973583	0.973544	0.973524
300	0.973618	0.973579	0.973539	0.973519
330	0.973615	0.973576	0.973537	0.973517
360	0.973613	0.973574	0.973534	0.973515
MTBF	**351.0655**	**351.0737**	**351.0811**	**351.0881**

Caption: table 4: Impact of mixer repair rate on system dependability

v) Reliability of the network is affected by the actuator repairing frequency (μ_2).

The analysis makes adjustments to μ_2 at 0.030, 0.032, 0.034, and 0.036 to examine the effect of the extruder's replacement rate on reliability of the system. λ_1=0.0027, λ_2=0.0005, λ_3=0.0009, λ_4=0.0011, γ=0.0054, μ_1=4.800, μ_3=0.0999, μ_4=0.4999, and δ=12.000 are the balance of constants. Table 1 displays the results of the calculation of the system's reliability. The results show that when the extruder's replacement rate increases from 0.030 to 0.036, the system's reliability decreases by roughly 0.07% to 0.27% and its Mean Time Without Failures (also known as MTBF) decreases by 0.2%.

Table 5

ρ→ DAYS ↓	**0.030**	**0.032**	**0.034**	**0.036**
30	0.979090	0.979332	0.979566	0.979791
60	0.974817	0.975374	0.975895	0.976384

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90	0.973239	0.974003	0.974703	0.975346
120	0.972604	0.973482	0.974275	0.974993
150	0.972342	0.973278	0.974115	0.974866
180	0.972232	0.973195	0.974052	0.974818
210	0.972185	0.973160	0.974025	0.974797
240	0.972163	0.973144	0.974012	0.974786
270	0.972152	0.973135	0.974005	0.974780
300	0.972146	0.973130	0.974001	0.974777
330	0.972142	0.973127	0.973998	0.974774
360	0.972140	0.973125	0.973996	0.974772
MTBF	**350.6466**	**350.9391**	**351.2011**	**351.4370**

Caption: table 5: Impact of extruder repair rate on system dependability

vi) Impact of the repair rate of the spray cooling bath (δ) on system dependability.

The effects of the chilled spray water and sub-system replacement rate on the system's reliability are being investigated by changing these numbers to δ = 8.000, 10,000, 12,000, and 14,000, respectively. The following are the other sub-systems' breakdown and replacement increases:

The breakdown and substitute rates of return for the other sub-systems are as follows: λ_1 = 0.0027, λ_2 = 0.0005, λ_3 = 0.0009, λ_4 = 0.0011, γ = 0.0054, μ_1 = 4.800, μ_2 = 0.030, μ_3 = 0.0999, μ_4 = 0.4999. The outcome of calculating the system's reliability are displayed in Table 4.1(f). According to this tabletop, the system's reliability decreases by about 0.6% as the length increases from 30 to 360 days. When conditioning tape maintenance rates are increased from 8,000 to 14,000, dependability improves from 0.0039% to 0.014% and MTBF improves by 0.01%.

Table 6

ρ→ **DAYS**↓	**8**	**10**	**12**	**14**
30	0.979420	0.979438	0.979450	0.979458
60	0.975588	0.975618	0.975639	0.975653
90	0.974295	0.974334	0.974361	0.974379
120	0.973711	0.973857	0.973888	0.973910

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150	0.973623	0.973674	0.973708	0.973732
180	0.973545	0.973599	0.973636	0.973662
210	0.973510	0.973567	0.973605	0.973632
240	0.973493	0.973551	0.973590	0.973619
270	0.973483	0.973543	0.973583	0.973612
300	0.973477	0.973538	0.973579	0.973608
330	0.973473	0.973535	0.973576	0.973605
360	0.973470	0.973532	0.973574	0.973604
MTBF	**351.0451**	**351.0622**	**351.0737**	**351.0818**

Caption: table 6: Impact of repair rate of spray cooling bath on system dependability

A CONSISTENT CONDITION

The impact of various variables on long-term accessibility is examined in the following paragraphs. Again, not all conceivable combinations of the regulating components of the structure have been considered; however, some that have a more significant effects on the organization were previously researched.

(a) Impact of blender and shredder malfunction percentages on systems reliability throughout the extended run

Let $\lambda_3 = 0.0009$, $\lambda_4 = 0.0011$, $\gamma = 0.0054$, $\mu_1 = 4.800$, $\mu_2 = 0.033$. $\mu_3 = 0.0999$, $\mu_4 = 0.4999$, and $\beta = 12.000$, with different compressor and blender failure rates occurred outlined below: $\lambda_1 = 0.0025, 0.0027, 0.0029, 0.0030$; $\alpha_2 = 0.0003, 0.0005, 0.0007$, and 0.0009. Applying solution (4.20), the structure's long-term accessibility has been determined. Table 7 displays the system's reliability over time for various mixer and extrusion breakdown rates configurations. According to a table examination, the extruder's breakdown frequency λ_2 has an estimated 1.7% influence on long-term accessibility, while the raw mixer's failure rate λ_1 has a projected 0.010% impact.

Table 7

$\lambda_1 \rightarrow$ $\lambda_2 \downarrow$	0.0025	0.0027	0.0029	0.0030
0.0003	0.979388	0.979348	0.979308	0.979288
0.0005	0.973608	0.973569	0.973530	0.973510
0.0007	0.967897	0.967858	0.967819	0.967800
0.0009	0.962253	0.962214	0.962175	0.962156

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Caption: table 7: Impact of subsystem failure rates of the mixer and extruder on the long-term availability of the system

1. How fixing the mixing system and extrusion equipment will affect the system's long-term functionality?

Utilizing $\lambda_1 = 0.0027$, $\lambda_2 = 0.0005$, $\lambda_3 = 0.0009$, $\lambda_4 = 0.0011$, $\gamma = 0.0054$, $\mu_3 = 0.0999$, and $\mu_4 = 0.4999$, and using formula (4.20), we have determined the system's durability for different blender and shredder maintenance rate pairings outlined below: λ2 = 0.030, 0.032, 0.034, and 0.036; μ_1 = 4.6, 4.8, 5.0, and 5.2. Table 8 displays the computed long-term accessibility. According to a table examination, the extruder's maintenance rate (μ_2) affects the system's durability by about 0.27%, and its replacement rate (μ_1) affects it by about 0.0067%. In comparison to μ_1, μ_2 has a stronger influence.

TABLE 8

$\mu_1 \rightarrow$ $\mu_2 \downarrow$	4.6	4.8	5.0	5.2
0.030	0.972112	0.972135	0.972156	0.972176
0.032	0.973097	0.973120	0.973142	0.973161
0.034	0.973968	0.973992	0.974013	0.974033
0.036	0.974744	0.974767	0.974789	0.974808

Caption: table 8: Impact of repair rates of subsystems, namely the mixer and extruder, on the long-term availability of the system.

Effects of conditioning tap breakdown and maintenance frequencies on the system's durability

Utilizing $\lambda_1 = 0.0027$, $\lambda_2 = 0.0005$, $\lambda_3 = 0.0009$, $\lambda_4 = 0.0011$, $\mu_1 = 4.800$, $\mu_2 = 0.033$, $\mu_3 = 0.0999$, $\mu_4 = 0.4999$, For the above different combinations of conditioning tap breakdown and maintenance interest rates, we have computed the system's long-term accessibility using the following method:

$\delta = 8, 10, 12, 14$; $\gamma = 0.0050, 0.0052, 0.0054, 0.0056$. Table 9 presents the results. A review of this table shows that chilling tap breakdown rate (γ) affects durability by about 0.0036% to 0.002%, while restoration rate (δ) affects it by about 0.015%.

Table 9

$\rho \rightarrow$ $r \downarrow$	8	10	12	14
0.0050	0.973486	0.973545	0.973585	0.973613

0.0052	0.973474	0.973536	0.973577	0.973606
0.0054	0.973462	0.973526	0.973569	0.973600
0.0056	0.973451	0.973517	0.973561	0.973593

Caption: table 9: Impact of subsystem failure rates in the spray cooling bath on the long-term availability of the system

Effects of printer service and failure probabilities affect the system's reliability over time

Given $\lambda_1 = 0.0027$, $\lambda_3 = 0.0009$, $\lambda_4 = 0.0011$, $\gamma = 0.0054$, $\mu_1 = 4.8$, $\mu_3 = 0.0999$, $\mu_4 = 0.4999$, and $\delta = 12$, The system's stability for the extruder's failures and replacement frequencies has been determined in the following manner: λ_2= 0.0003, 0.0005, 0.0007, 0.0009; μ_2=0.030, 0.032, 0.034, 0.036. The outcome of this computation is shown in Table 10, which also shows how the extruder's fail and maintenance rates affect the system's long-term unavailability. This table shows that longevity is more affected by the extruder's maintenance rate (μ_2) than by the breakdown rate (λ_2). λ_2's impact on accessibility varies from 0.16% to 0.48%. The value of μ_2 ranges from 1.6% to 2.0%.

Table 10

$\lambda_2\rightarrow$ $\mu_2\downarrow$	0.0003	0.0005	0.0007	0.0009
0.030	0.978476	0.972135	0.975875	0.979696
0.032	0.979075	0.973120	0.977238	0.971426
0.034	0.979604	0.973992	0.978443	0.972957
0.036	0.970075	0.974767	0.979517	0.974323

Caption: table 10: Impact of failure and repair rates of extruder subsystems on the long-term availability of the system

Conclusion:

This research has successfully developed a comprehensive mathematical framework for reliability analysis in plywood production facilities. This framework integrates the analytical prowess of Laplace transforms with the computational efficiency of the fourth-order Runge-Kutta method (RK4). The study not only significantly advances theoretical reliability engineering but also offers substantial contributions to practical industrial applications (see[27-47]).

According to a comparison of tables 1 through 6 and 7 through 10, the extruder, or sub-system B, has the greatest effect on the long-term dependability of the entire network.accessibility. The reliability analysis can also be used to confirm how subsystem B's breakdown and restoration patterns affect the reliability of the system. As described in earlier sections, we have also used the fourth-order Runge-Kutta approach to confirm similar findings in Diagrams 1

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and 2. The other components contribute nearly equally to the system's longevity and reliability. This pattern has been observed in all of the facility's data. Therefore, in order to improve the system's overall trustworthiness and long-term accessibility, managers should concentrate more on sub-system B. Using the procedure described in section (2.7), we can once more ascertain the extruder's ideal replacement frequency.

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