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Research paper

Evaluating The Reliability and Availability of A High-Pressure Die Casting System Featuring Two Units and Cold Standby Redundancy

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Abstract

This study presents a behavioral and availability analysis of a high-pressure die casting plant modelled as a two-unit system with cold standby redundancy. By investigating the effects of varying repair rates (α) on system availability, we demonstrate that increased repair rates correlate positively with availability, aligning with practical expectations in industrial applications. Application of the regenerative graphical technique (based on the center of pressure) allows for evaluating the parameters very quickly without involving the computation of state equations or resultants. Our analysis highlights the potential inclusion of multi-unit systems with perfect and imperfect switch-over devices to broaden the model's applicability. Additionally, insights are provided for conditions under which failure and repair rates may vary, offering directions for future profit-and-loss analysis. We discuss how operational costs can be minimized by leveraging expertise gained through repeated server visits, thereby reducing the need for primary interventions. This study offers a flexible framework for evaluating various system states and assessing key performance attributes, with implications for cost-effective maintenance strategies in industrial settings.

Keywords: *High Pressure Die Casting; RPGT; Failure Rate; Industrial Maintenance Strategies; System Availability.*

1. Introduction

Reliability performance measures are critical across various industrial applications, including urea fertilizer plants, power plants, manufacturing frameworks, and engineering systems (Sahu et al., 2024). To sustain high levels of reliability, these systems commonly rely on efficient repair and maintenance strategies, supported by standby redundant components, to ensure consistent operation (Kumar et al., 2019). In specific industrial settings, such as steel manufacturing plants, online units must maintain high availability, with redundant units acting as reliable backups when necessary (Al Rahbi et. al., 2019). In high-pressure die casting, molten metal is injected into a pre-designed mold at high pressure, solidifies upon cooling, and is subsequently ejected from the mold. There are four main theoretical stages in this process: preparing the mould, pouring the composition, disbanding the mould, and performing the cabal countering. The solidified metal is released from the mold using ejector pins, and trimming is performed to remove excess material, which is recyclable. For systems like the HPDC plant, the perfect switchover device seamlessly alternates between the primary and standby units, enhancing system reliability and cost-efficiency (Renu and Bhatia, 2019). Banerjee et. al. (2024) have applied the Sine Cosine Algorithm to solve reliability problems. Garg et. al. (2022) have inspected briquette macjine with different faults. Standby redundancy is a resilience strategy where a secondary unit remains inactive until the primary unit fails, at which point it takes over (Rajbala & Khurana, 2022). This setup, illustrated in systems with identical parallel components, is commonly applied in manufacturing and mechanical systems due to its ability to sustain operations without significant interruptions (Ma et al., 2020). For example, two identical units of the subsystem C_1 are connected in parallel. Only one unit of C_1 is working, and the other unit of C_1 is in standby mode. It will turn on when the first unit of C_1 fails. Standby redundancy is more suited to manufacturing systems, mechanical systems, etc.

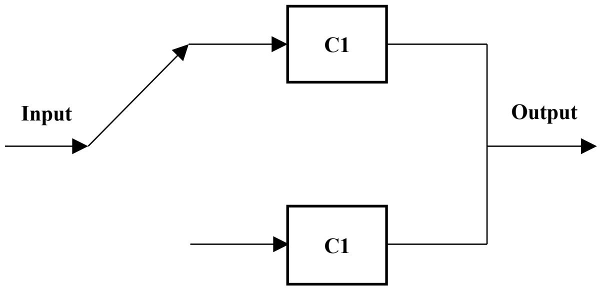

Fig. 1: Standby Redundancy.

It is redundancy, where the standby unit is operational in place of the main unit; such kind of redundancy is called standby redundancy.
High-pressure die casting is particularly valuable in industries such as automotive, aerospace, and medical manufacturing, where complex metal parts must be produced with high precision (Abdul Jawwad & AbuNaffa, 2022). The HPDC technique is favoured for its cost-effectiveness, operational convenience, minimal material waste, and compatibility with intricate design specifications (Kumar et. al., 2019). This study's findings aim to contribute to the broader body of knowledge on reliability analysis, particularly within manufacturing systems that demand stringent operational continuity and efficiency.
This study examines the behavioural and availability analysis of a high-pressure die casting (HPDC) plant, which utilizes a two-unit system with cold standby redundancy and a perfect switchover device. In the current research, the Regenerative Point Graphical Technique or RPGT is used to determine the value; the essential parameters of the system. RPGT allows for a streamlined assessment of transition probabilities and mean sojourn times by defining primary, secondary, and tertiary circuits in the system's transition diagram (Kaur et al., 2023). This method is advantageous, especially in systems with multiple states, as it simplifies parameter calculations without requiring complex recursive solutions of state equations. By establishing a base state, RPGT enables a more efficient analysis of key reliability measures, avoiding the otherwise cumbersome process of equation derivation, Laplace transforms, and simplifications.

2. Rationale behind the study

This study is essential due to the operational challenges of maintaining consistent quality and reliability in high-pressure die casting (HPDC) plants, especially in industries like automotive, aerospace, and medical device manufacturing that require intricate metal parts with precise tolerances. High-pressure die casting is a highly applicable pressure die casting technology used in several significant sectors to produce metal parts with intricate designs. However, mould preparation involves cleaning the mould to get rid of contaminants that could lower the quality of the metal cast. It also entails lubricating the internal walls of the mould to facilitate simpler ejection from the mould and temperature control. To keep the plant operating under such circumstances, the online unit may need to be offline with the aid of a flawless switch-over device, and the redundant unit may need to be made online with the aid of the same equipment. The use of the Regenerative Point Graphical Technique (RPGT) enables a streamlined evaluation of these reliability factors, offering a scalable framework for ensuring high-quality production in HPDC plants while minimizing interruptions and maximizing system availability.

3. Data analysis

3.1. System description

The high-pressure die casting system has a module A running, attached to it, a module B on standby, and a perfect switch over device, which, in case the A module fails D module B activates with the help of a perfect switch over device. When it comes down to the logic of a determinate failure unit, it all comes down to the decision as to whether the failure criterion of the unit in question was met. There is a single server that is 24x7 hours available, which serves and maintains all units in the system. It is the duty of the switch-over device to keep the system running for optimum upkeep values of system parameters. The unit's failure and repair rates are given below.

Assumptions

1) Failure rates of units follow an exponential distribution.
2) Repair rates have general distributions.
3) Switching is perfect and may fail.
4) There is a single server that is 24x7 hours available.

Notations

$\left(i \xrightarrow{sr} j\right)$: r-th directed simple path from i-state to j-state; where r takes different positive integral values for different paths.

$\left(\xi \xrightarrow{sff} i\right)$: An unbranching path, flawlessly appropriate from ξ -state to i-state.

$V_{m,m}$: The probability factor of such a state becomes visible when it is improved with
m to obtain the so-called given state with M cycle.

$V_{\overline{m,m}}$: Probability factor of the state m reachable from the terminal state m of the
$m - \overline{\text{cycle}}$.

R_i (t): Reliability of the system at time t, started at t = 0, in the good regenerative state 'i.'

A_i (t) : Probability of the availability of the system at time 't' if the system enters.
Regenerative state 'i' at t = 0.

B_i (t): Reliability that the server is busy for doing a particular job at Time 't'; given,
that the system entered regenerative state 'i' at t = 0.

V_i (t) : Expected server visits in (0,t] given the system starts in regenerative state i at t=0

'' : Dash denotes derivative.

$\mu_i = \int_0^\infty R_i(t)dt$

n_i : Expected waiting time spent while doing a given job, given that the system entered regenerative state 'i' at t=0.
ξ: System's starting condition
f_j: Degree of Fuzziness associated with the j-state.
A: The main online unit in full capacity.
B: main online unit in full capacity.
a: the main online unit in a failed state.
b: the main online unit in a failed state.
S: Switch over device is good.
s: Switch over device failed.
$\lambda_{i:}$ = failure rate of units
λ : failure rate of switch
μ_i: Mean sojourn time
μ_i^1 : system waiting time to repair
ξ : Base state of the system
$\overline{G}, \overline{H}, g^*, f^{*\prime}, g^{*\prime}$
(i, j, k) A simple path through the vertices I, j, k.
$V_{i,j}$ Path probability in transiting from ith state to jth state.
f(t), h(t), g(t) are general repair rates of switch, mainline unit A, standby unit B.

3.2. System description

By considering the above assumptions and notations, the model's transition diagram is illustrated in Figure 2.

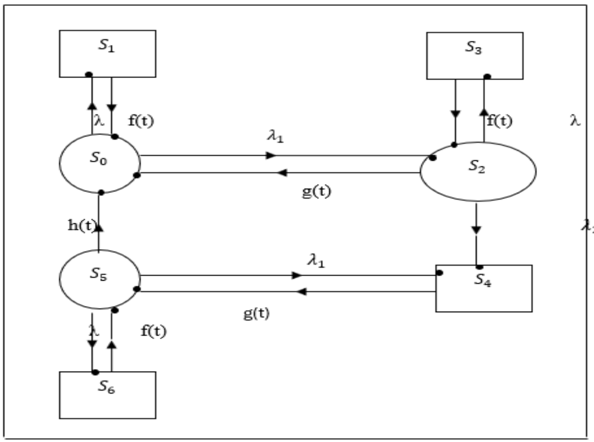

Fig. 2: Transition Diagram.

States: Using Markov Process the system can be in the following states

S_0=ABS, S_1 =Abs, S_2= aBS, S_3= aBs, S_4= abS, S_5= AbS, S_6= aBs

3.3. Evaluation of parameters of the system

When trying to determine the most efficient functioning of a complex system, the first thing to do is to decide what a "base state" is and fulfill properly the so-called RPGT procedure. The MTSF is set relative to the initial state of '0', and all other matrix elements are formed based on the base state.

3.3.1. Determination of base-state

Based on the provided transition diagram (Fig. 2) and per the detailed Table 1, it is possible to define the Primary, Secondary, and Tertiary circuits at every node.

Table 1: Primary, Secondary, Tertiary, Tetra Circuits, at A Vertex I

Vertex i	(CL1)	(CL2)	(CL3)	(CL4)
0	{0,1,0} {0,2,0} {0,2,4,5,0}	- {2,3,2} {2,3,2}, {4,5,4} {5,6,5}	- - - {5,6,5} -	- - - - -
1	{1,0,1}	{0,2,0} {0,2,4,5,0}	{2,3,2} {2,3,2},{4,5,4} {5,6,5}	- {5,6,5} -
2	{2,0,2} {2,3,2} {2,4,5,0,2}	{0,1,0} - {4,5,4},{5,6,5} {0,1,0}	- - {5,6,5}	-
3	{3,2,3}	{2,0,2} {2,4,5,0,2}	{0,1,0} {4,5,4} {5,6,5},{0,1,0}	- {5,6,5} -

4	{4,5,4} {4,5,0,2,4}	{5,6,5} {5,6,5} {0,1,0} {0,2,0} {2,3,2}	- {2,3,2}	-
5	{5,6,5} {5,4,5} {5,0,2,4,5}	- - {0,1,0} {0,2,0} {2,3,2}	- - {2,3,2}	- - -
6	{6,5,6}	{5,6,5} {5,0,2,4,5}	- {0,1,0} {0,2,0} {2,3,2}	- {2,3,2}

Source: Authors' own work.

Looking at the transition diagram in the figure, the primary circuits are distributed as follows about the vertices: three at vertex 0, one at vertex 1, three at vertex 2, one at vertex 3, two at vertex 4, three at vertex 5, and one at vertex 6. From these, three primary circuits are present at the vertices 0, 2, and 5, and therefore any of these vertices may be considered as a reference or base state for the problem. The specific secondary circuits on all arcs from the vertex 0 to a specific element location are as follows: {2, 3, 2}, {4, 5, 4}, and {5, 6, 5}. The system possesses one tertiary circuit {5, 6, 5}. There are also no higher-order circuits existing along the paths leading away from the vertex 0. Additionally, there are three primary circuits along with one supporting one being supplied from the vertices 2 and 5, respectively. there are no tertiary circuits in the system that would also help in considering the vertex 0 as the basic point. Different simple paths in the form of the transition diagram of the system are illustrated in Table 2, given below.

Table 2: Primary, Secondary, Tertiary Circuits W. R. T. the Simple Paths (Base-State '0')

Vertex j	$\left(0 \overset{S_r}{\rightarrow} j\right)$: (P0)	(P1)	(P2)	(P3)
1	$\left(0 \overset{S_1}{\rightarrow} 1\right)$: {0,1}	-	-	-
2	$\left(0 \overset{S_1}{\rightarrow} 2\right)$: {0,2}	{2,3,2}	-	-
3	$\left(0 \overset{S_1}{\rightarrow} 3\right)$: {0,2,3}	{2,3,2}	-	-
4	$\left(0 \overset{S_1}{\rightarrow} 4\right)$: {0,2,4}	{2,3,2} {4,5,4}	{5,6,5}	-
5	$\left(0 \overset{S_1}{\rightarrow} 5\right)$: {0,2,4,5}	{2,3,2} {4,5,4} {5,6,5}	{5,6,5}	-
6	$\left(0 \overset{S_1}{\rightarrow} 6\right)$: {0,2,4,5,6}	{2,3,2} {4,5,4} {5,6,5}	{5,6,5}	-

Source: Authors' own work.

3.4. Transition probabilities and the mean sojourn times

3.4.1. Transition probabilities

The transition path probabilities from various vertices using RPGT to other states are given in below Table 3. Here, $p_{i,j} = q^{*}_{i,j}(0)$ = L $[q_{i,j}(t)]$, where L and * denote the Laplace Transformation

Table 3: Transition Probabilities

$q_{i,j}(t)$	$p_{i,j} = q^{*}_{i,j}(0)$
$q_{0,1}(t) = \lambda e^{-(\lambda+\lambda_1)t}$ $q_{0,2}(t) = \lambda_1 e^{-(\lambda+\lambda_1)t}$	$p_{0,1} = \frac{\lambda}{\lambda+\lambda_1}$ $p_{0,3} = \frac{\lambda_1}{\lambda+\lambda_1}$
$q_{1,0}(t) = f(t)$	$p_{1,0} = f^{*}(0)$
$q_{2,0}(t) = g(t)e^{-(\lambda+\lambda_2)t}$ $q_{2,4}(t) = \lambda_2 e^{-(\lambda+\lambda_2)t}\overline{G}(t)$ $q_{2,3}(t) = \lambda e^{-(\lambda+\lambda_2)t}\overline{G}(t)$	$p_{2,0} = g^{*}(\lambda+\lambda_2)$ $p_{2,4} = \frac{\lambda_2}{\lambda+\lambda_2}\{1-g^{*}(\lambda+\lambda_2)\}$ $p_{2,3} = \frac{\lambda}{\lambda+\lambda_2}\{1-g^{*}(\lambda+\lambda_2)\}$
$q_{3,2}(t) = f(t)$	$p_{3,2} = f^{*}(0)$
$q_{4,5}(t) = g(t)$	$p_{4,5} = g^{*}(0)$
$q_{5,0}(t) = h(t)e^{-(\lambda+\lambda_1)t}$ $q_{5,4}(t) = \lambda_1 e^{-(\lambda+\lambda_1)t}\overline{H}(t)$ $q_{5,6}(t) = \lambda e^{-(\lambda+\lambda_1)t}\overline{H}(t)$	$p_{5,0} = h^{*}(\lambda+\lambda_1)$ $p_{5,4} = \frac{\lambda_1}{\lambda+\lambda_1}\{1-h^{*}(\lambda+\lambda_1)\}$ $p_{5,6} = \frac{\lambda}{\lambda+\lambda_1}\{1-h^{*}(\lambda+\lambda_1)\}$
$q_{6,5}(t) = f(t)$	$p_{6,5} = f^{*}(0)$

Source: Authors' own work.

It can be easily verified that.

$p_{0,1} + p_{0,2} = 1.$

$p_{1,0} = 1.$

$p_{2,0} + p_{2,3} + p_{2,4} = 1.$

$p_{3,2} = f^{*}(0) = 1.$

$p_{4,5} = g^*(0) = 1.$

$p_{5,0} + p_{5,4} + p_{5,6} = 1.$

$p_{6,5} = f^*(0) = 1$

3.4.2. Mean sojourn times

The mean sojourn time for various states using RPGT is given below in Table 4.

Here, $\mu_i = L[Ri(t)] = R_i^*(0)$, where L and * denote Laplace transformation.

Table 4: Mean Sojourn Times

$R_i(t)$	$\mu_i = R_i^*(0)$
$R_0(t) = e^{-(\lambda+\lambda_1)t}$	$\mu_0 = \frac{1}{\lambda+\lambda_1}$
$R_1(t) = \bar{F}(t)$	$\mu_1 = -f^{*\prime}(0)$
$R_2(t) = e^{-(\lambda+\lambda_2)t}\bar{G}(t)$	$\mu_2 = \frac{1-g^*(\lambda+\lambda_2)}{(\lambda+\lambda_2)}$
$R_3(t) = \bar{F}(t)$	$\mu_3 = -f^{*\prime}(0)$
$R_4(t) = \bar{G}(t)$	$\mu_4 = -g^{*\prime}(0)$
$R_5(t) = e^{-(\lambda+\lambda_1)t}\bar{H}(t)$	$\mu_5 = \frac{1-h^*(\lambda+\lambda_1)}{(\lambda+\lambda_1)}$
$R_6(t) = \bar{F}(t)$	$\mu_6 = -f^{*\prime}(0)$

Source: Authors' own work.

3.5. Evaluation of parameters

Using "0" as the base state of the system, we estimate the expected value of the time to failure, and all the other parameters are developed under the conditions of permanent operation. On the basis of the Regenerative Point Graphical Technique (RPGT) the formulas for the development of the operational systems performance measures was build.
The possible transitions of the state "0" stem are:

$V_{0,0} = 1$

$V_{0,1} = (0,1) = p_{0,1}$

$$V_{0,2} = \frac{(0,2)}{1-L_2} = \frac{p_{0,2}}{1-p_{2,3}}$$

$$V_{0,3} = \frac{(0,2,3)}{1-L_2} = \frac{p_{0,2}p_{2,3}}{1-p_{2,3}}$$

$$V_{0,4} = \frac{(0,2,4)}{(1-L_2)\left(1-\frac{L_4}{1-L_5}\right)} = \frac{p_{0,2}p_{2,4}(1-p_{5,6})}{p_{5,0}(1-p_{2,3})}$$

$$V_{0,5} = \frac{(0,2,4,5)}{(1-L_2)\left(1-\frac{L_4}{1-L_5}\right)(1-L_5)} = \frac{p_{0,2}p_{2,4}}{p_{5,0}(1-p_{2,3})}$$

$$V_{0,6} = \frac{(0,2,4,5,6)}{(1-L_2)\left(1-\frac{L_4}{1-L_5}\right)(1-L_5)} = \frac{p_{0,2}p_{2,4}p_{5,6}}{p_{5,0}(1-p_{2,3})}$$

Where,

$1 - L_2 = 1 - \{2,3,2\} = 1 - p_{2,3}p_{3,2} = 1 - p_{2,3}$

$1 - L_4 = 1 - \{4,5,4\} = 1 - p_{4,5}p_{5,4} = 1 - p_{5,4}$

$1 - L_5 = 1 - \{5,6,5\} = 1 - p_{5,6}p_{6,5} = 1 - p_{5,6}$

$1 - L_4 - L_5 = 1 - \{4,5,4\} - \{5,6,5\} = 1 - p_{4,5}p_{5,4} - p_{5,6}p_{6,5} = 1 - p_{5,4} - p_{5,6} = p_{5,0}$

a) Mean Time to System Failure (T_0): From Fig. 2, the regenerative and unfailed states through which a system can move (from the initial state '0') before going to any failed state are: i = 0, 2. When the initial state is zero at RPGT, the average time to system failure is given by:

$$\text{MTSF} = \left[\sum_{i,s_r}\left\{\frac{\left\{pr\left(\xi \xrightarrow{sr(sff)} i\right)\right\}.\mu_i}{\prod_{k_1\neq\xi}\left\{1-V_{\overline{k_1,k_1}}\right\}}\right\}\right] \div \left[1-\sum_{s_r}\left\{\frac{\left\{pr\left(\xi \xrightarrow{sr(sff)} \xi\right)\right\}}{\prod_{k_2\neq\xi}\left\{1-V_{\overline{k_2,k_2}}\right\}}\right\}\right]$$

$T_0 = [(0,0)\,\mu_0 + (0,2)\,\mu_2] \div [1 - L_0]$

$= [(0,0)\ \mu_0 + (0,2)\ \mu_2] \div [1 - p_{0,2}p_{2,0}] = N \div D$

Where, $L_0 = (0,2,0) = p_{0,2}p_{2,0}$

$N = [(0,0)\ \mu_0 + (0,2)\ \mu_2] = p_{0,0}\mu_0 + p_{0,2}\mu_2 = \mu_0 + p_{0,2}\mu_2$

$D = [1 - L_0] = 1 - p_{0,2}p_{2,0}$

b) Availability of the system (A_0): The regenerative states, at which the system is available are j = 0, 2 and 5 and the regenerative states are i = 0 to 6. Using RPGT for base state 'ξ' = '0'

$$A_0 = \left[\Sigma_{j,s_r}\left\{\frac{\{pr(\xi \xrightarrow{s_r} j)\} f_j . \mu_j}{\Pi_{k_1 \neq \xi}\{1 - V_{k_1,k_1}\}}\right\}\right] \div \left[\Sigma_{i,s_r}\left\{\frac{\{pr(\xi \xrightarrow{s_r} i)\} . \mu_i^1}{\Pi_{k_2 \neq \xi}\{1 - V_{k_2,k_2}\}}\right\}\right]$$

$A_0 = \left[\Sigma_j V_{\xi,j} . f_j . \mu_j\right] \div \left[\Sigma_i V_{\xi,i} . \mu_i^1\right]$

$= (V_{0,0}\ \mu_0 + V_{0,2}\ \mu_2 + V_{0,5}\ \mu_5) / (V_{0,0}\ \mu_0 + V_{0,1}\ \mu_1 + V_{0,2}\ \mu_2 + V_{0,3}\ \mu_3 + V_{0,4}\ \mu_4 + V_{0,5}\ \mu_5\ V_{0,6}\ \mu_6)$

c) Busy period of the Server (B_0): The regenerative states in which the server is busy while doing repairs are $1 \leq j \leq 6$; the regenerative states are: i = 0 to 6. Using RPGT for 'ξ' = '0'

$$B_0 = \left[\Sigma_{j,s_r}\left\{\frac{\{pr(\xi \xrightarrow{s_r} j)\} . \eta_j}{\Pi_{k_1 \neq \xi}\{1 - V_{k_1,k_1}\}}\right\}\right] \div \left[\Sigma_{i,s_r}\left\{\frac{\{pr(\xi \xrightarrow{s_r} i)\} . \mu_i^1}{\Pi_{k_2 \neq \xi}\{1 - V_{k_2,k_2}\}}\right\}\right]$$

$B_0 = \left[\Sigma_j V_{\xi,j} . \eta_j\right] \div \left[\Sigma_i V_{\xi,i} . \mu_i^1\right]$

$= (V_{0,1}\ \mu_1 + V_{0,2}\ \mu_2 + V_{0,3}\ \mu_3 + V_{0,4}\ \mu_4 + V_{0,5}\ \mu_5\ V_{0,6}\ \mu_6) / (V_{0,0}\ \mu_0 + V_{0,1}\ \mu_1 + V_{0,2}\ \mu_2 + V_{0,3}\ \mu_3 + V_{0,4}\ \mu_4 + V_{0,5}\ \mu_5\ V_{0,6}\ \mu_6)$

d) Expected number of Server's visits (V_0): The Regenerated states at which the server makes a return visit for system repair are j = 1, 2; the regenerated states are; i = 0 to 6. The application of an RPGT for the 0-level base state 'ξ' is : (25)

$$V_0 = \left[\Sigma_{j,s_r}\left\{\frac{\{pr(\xi \xrightarrow{s_r} j)\}}{\Pi_{k_1 \neq \xi}\{1 - V_{k_1,k_1}\}}\right\}\right] \div \left[\Sigma_{i,s_r}\left\{\frac{\{pr(\xi \xrightarrow{s_r} i)\} . \mu_i^1}{\Pi_{k_2 \neq \xi}\{1 - V_{k_2,k_2}\}}\right\}\right]$$

$V_0 = \left[\Sigma_j V_{\xi,j}\right] \div \left[\Sigma_i V_{\xi,i} . \mu_i^1\right]$

$= (V_{0,1} + V_{1,2}) / (V_{0,0}\ \mu_0 + V_{0,1}\ \mu_1 + V_{0,2}\ \mu_2 + V_{0,3}\ \mu_3 + V_{0,4}\ \mu_4 + V_{0,5}\ \mu_5\ V_{0,6}\ \mu_6)$

3.6. Profit function of the system

The Profit analysis of the system can be done by using the profit function:

$P_0 = C_1 . A_0 - C_2 . B_0 - C_3 . V_0$

Here in this equations, the variables meant:
C_1 = Revenue per unit of time the system is available.
C_2 = Cost per unit of time that a server is busy performing work related to fixing a failure
C_3 = Cost per visit of the server.

3.7. Particular cases

i) When repair rates of units follow exponential distributions, then take.

$g(t) = \alpha e^{-\alpha t}$, $h(t) = \beta e^{-\beta t}$, $f(t) = \omega e^{-\omega t}$

We have,

$p_{0,1} = \frac{\lambda}{\lambda+\lambda_1}$, $p_{0,2} = \frac{\lambda_1}{\lambda+\lambda_1}$, $p_{1,0} = 1$, $p_{2,0} = \frac{\alpha}{\alpha+\lambda+\lambda_2}$, $p_{2,3} = \frac{\lambda}{\alpha+\lambda+\lambda_2}$, $p_{2,4} = = \frac{\lambda_2}{\alpha+\lambda+\lambda_2}$

, $p_{3,2} = 1$, $p_{4,5} = 1$, $p_{5,0} = \frac{\beta}{\beta+\lambda+\lambda_1}$, $p_{5,4} = \frac{\lambda_1}{\beta+\lambda+\lambda_1}$, $p_{5,6} = \frac{\lambda}{\beta+\lambda+\lambda_1}$, $p_{6,5} = 1$

$\mu_0 = \frac{1}{\lambda+\lambda_1}$, $\mu_1 = \frac{1}{\omega}$, $\mu_2 = \frac{1}{\alpha+\lambda+\lambda_2}$, $\mu_3 = \frac{1}{\omega}$, $\mu_4 = \frac{1}{\alpha}$, $\mu_5 = \frac{1}{\beta+\lambda+\lambda_1}$, $\mu_6 = \frac{1}{\omega}$

By using these results, we get the following:
ii) For Warm Stand-by case:
Taking $0 < \lambda_2 < \lambda_1$.s
Results can be derived accordingly.

iii) For Hot Stand-by:
Taking $\lambda_2 = \lambda_1$.
Results can be derived accordingly.

4. Discussion of results

The following tables, graphs and conclusions are obtained for:

4.1. MTSF vs. repair rate

On taking, λ_2= 0.005; $\lambda = 0.01$
MTSF of the UPS can be determined by varying the combinations of the Failure Rate (λ_1) with λ_1 = 0.005, 0.006, 0.007, 0.008, 0.009, and 0.01 when α = 0.8, 0.85, 0.90, 0.95, 1.0. Measuring MTSF for the initial state "β" of the RPGT which refers to "0" as:
The data obtained are shown in Table 5 and graphically in Fig. 3.

Table 5: Mean Time to System Failure

$\lambda_{1\downarrow}\backslash\ \alpha \rightarrow$	0.80	0.85	0.90	0.95	1.0
0.005	99.6961	99.7132	99.7293	99.7433	99.7551
0.006	99.6362	99.6563	99.6753	99.6924	99.7074
0.007	99.5764	99.6002	99.6221	99.6412	99.6584
0.008	99.5163	99.5444	99.5683	99.5901	99.6103
0.009	99.4564	99.4874	99.5152	99.5403	99.5624
0.01	99.3972	99.4321	99.4621	99.4903	99.5142

Source: Authors' own work.

Table 5 lays out the behavior of the MTSF (T0) on the repair rate of various systems for different values of the Failure Rate (λ_1) and repair rates. On viewing the rows of above table, it is concluded that as λ1↓ increases from 0.005 to 0.01, MTSF generally decreases, indicating shorter lifespans and thus lower reliability at higher λ1↓ values. Conversely, as α rises from 0.80 to 1.0, MTSF values tend to increase, suggesting that higher α correlates with greater reliability and longer system lifespans. But the change is not very much significant, while viewing the various columns from top to bottom the value of MTSF decreases. Hence, optimum value of MTSF failure rates of units should be kept minimum.

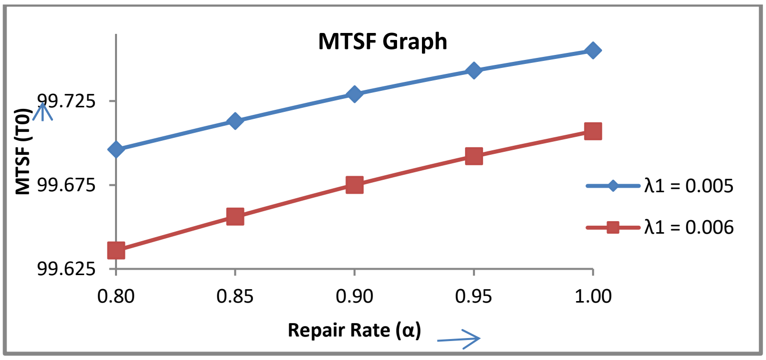

Fig. 3: Mean Time to System Failure.

Fig. 3 indicates that Mean Time to System Failure (MTSF) demonstrates a positive correlation with the increase in T0 for different failure rates (λ = 0.005 and 0.006). Specifically, as the repair rate (α) improves, the MTSF also increases, suggesting that a more efficient repair process allows the system to operate longer before experiencing a failure. This relationship highlights the importance of repair rates in enhancing system reliability, indicating that systems with quicker repair capabilities can significantly extend their operational lifespan, even when facing certain failure rates.

4.2. Availability (A_0) vs. the repair rate (α)

On taking, λ_2= 0.005; $\lambda = 0.01$; $\beta = 0.80$; $\omega = 0.80$.
The system Availability is determined for different failure rates (λ_1) as λ_1 = 0.005, 0.006, 0.007, 0.008, 0.009 and 0.01 and for the different repair rate (α) values as α = 0.80, 0.85, 0.90, 0.95 and 1.0. They are tabulated in the form of data in 6 and the graphical representation in Fig. 4.

Table 6: Availability of the System

λ_1	0.80	0.85	0.90	0.95	1.0
0.005	0.98761	0.98762	0.98762	0.98762	0.98763
0.006	0.98761	0.98761	0.98761	0.98762	0.98763
0.007	0.98760	0.98760	0.98761	0.98761	0.98762
0.008	0.98759	0.98760	0.98760	0.98761	0.98761
0.009	0.98758	0.98759	0.98760	0.98760	0.98761
0.01	0.98757	0.98758	0.98759	0.98760	0.98760

Source: Authors' own work.

The data presented in Table 6 describes the relationship between two different failure rates, namely, 0.005 and 0.01 lambda, and the reliability values between 0.80 and 1.0 sigma limits in terms of percent coverage of 90% for each reliability level in multiple parameters.

The values, which consistently hover around 0.9875 to 0.9876, indicate that the system maintains a high level of reliability regardless of the failure rate. Although there is a slight decrease in reliability as the failure rate increases, the changes are minimal, suggesting that the system demonstrates robust performance even under varying operational conditions. This resilience indicates effective design and engineering, allowing the system to perform reliably despite slight increases in failure rates.

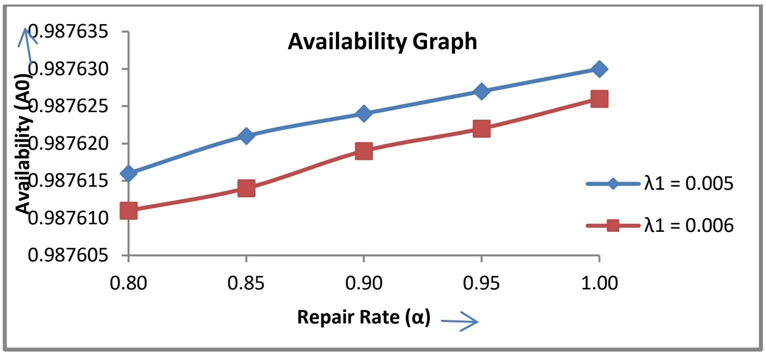

Fig. 4: Availability of the System.

Fig. 4 demonstrates that the availability (A_0) follows the expected trend for different failure rates ($\lambda 1=0.005$ and 0.0060), showing an increase as the repair rate (α) rises

5. Implications of study

The current study contributes to more effective and economically viable maintenance approaches in high-pressure die casting operations, offering a robust model with potential for adaptation and future expansion in reliability engineering. The study demonstrates that higher repair rates (α) lead to improved system availability, highlighting the importance of prioritizing efficient and responsive repair processes. This insight can guide maintenance planning to optimize uptime in high-pressure die casting plants. Secondly, by applying the regenerative-point graphical technique, the study provides a streamlined method for analyzing system parameters without requiring complex state equations. This technique offers a practical tool for industry professionals, allowing for quicker assessments and adjustments. Thirdly, by using the regenerative-point graphical technique, the study provides a streamlined method for analyzing system parameters without requiring complex state equations. This technique offers a practical tool for industry professionals, allowing for quicker assessments and adjustments. Fourth, the application of any system state as the base state for analysis allows a versatile evaluation of system attributes. This flexibility aids in understanding performance metrics under diverse conditions, making the model adaptable to various industrial contexts and objectives.

6. Future scope of study

The future research will be able to provide an extensive insight into the understanding of system reliability and maintenance towards improved operational efficiency, that can ultimately result in cost reduction for numerous real-world industrial applications. The behavior of multiple unit systems may be the subject of future research, with greater attention to both perfect and imperfect switch-over devices as regards system performance and overtime degradation in availability. In real systems, assuming perfect switchover—instant, flawless, and cost-free transitions can oversimplify actual behaviour.

Imperfect switchover devices reflect practical issues like time delays and transient states during switching. These delays can reduce performance or cause instability in time-sensitive operations. Switching may involve unstable intermediate states not captured in ideal models.

Energy and cost penalties are common during transitions, lowering efficiency.

Frequent switching leads to mechanical wear, reducing long-term reliability.

Control strategies become more complex when transitions aren't seamless.

Signal errors or noise may be introduced during imperfect switchovers.

Accounting for these limitations improves model accuracy and robustness.

This makes research more applicable to real-world systems and engineering practices. This can involve such things as the development of simulations that allow us to model how these devices affect repair rates and ultimately system reliability. By further refining the RPGT method, researchers could scale it up to deal with more complicated systems and speedier decision-making processes. Future work could aim to estimate the financial costs of differing repair rates and maintenance schedules, providing guidance to organizations that wish to prioritize various resource allocations.

7. Conclusion

The α-value increases with ε-value, increasing operational readiness from the point of view of the system's development, and is positively perceived by the graphical presentations, and tabulated data. There may be situations in which multiple system statics are studied. There can also be perfect and imperfect type switches in the situation. The practice called regenerative point graphing shall be used to estimate the values of the parameters on the sketch without the necessity of forming the couplings' statements and similarly, without the phase of numerically evaluating the said coupling. Future research could examine how and under which conditions unit failure and repair rates can be modulated as well discuss profit-and-loss analysis. The system works with little maintenance cost as second visit is cheaper than the first, when server learns about dataset on each and every primary visit.

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