Performance Analysis of Continuous Casting System of Steel Industry

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Abstract

The continuous casting system is the most important to solidify the liquid steel in the steel industry. Steel is the backbone of civilization and modernization. So, there is a need to optimize the performance of continuous casting system of steel industry. Continuous casting system has six subsystems: "Pouring turret ladle", "Tundish", "Mold", "Water spray chamber", "Support roller" and "Torch cutter". Series configuration is used to arrange these subsystems. The subsystem "Pouring turret ladle" is having three similar units. These units are operating in parallel. The subsystems "Tundish", "Mold", "Water spray chamber" and "Support roller" have a single unit. The subsystem "Torch cutter" contains two identical units: one is operative and other keep in cold standby. For all subsystems, the distribution of repair rates and failure rates of continuous casting system are taken as arbitrary distributions. Analysis of continuous casting system has been done by using supplementary

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variable technique. The numerical results of reliability measure of continuous casting system in terms of availability and profit have been computed by assuming exponential, Rayleigh and Weibull distributions.

Keywords: Continuous casting system, availability analysis, profit analysis, supplementary variable technique, steel industry.

1 Introduction

Due to advancement in science and engineering technology, the different kinds of mechanical systems used in industries is improved to make production faster, simpler and more efficient with their minimum production cost. This can be possible by failure-free functioning of mechanical systems. But, the possibilities of failure of mechanical systems cannot be denied completely. So, reliability engineering plays a vital role to maintain worthless failure of mechanical equipment and to enhance the smooth functioning of the whole industry.

Several researchers and engineers have been paid attention to mechanical system of different industries such as Arora and Kumar (1997) presented the availability of steam and power generation systems by Markov birth-death process. Singh and Mahajan (1999) analyzed reliability of utensils manufacturing unit by using Laplace transformation. Gupta at al. (2007) analyzed reliability and availability of serial processes of plastic-pipe manufacturing plant by using Runge-Kutta fourth order method. Sharma et al. (2009a) developed a computer network system model by supplementary variable technique. Kumar et al. (2009b) evaluated the performance analysis of ammonia synthesis unit in a fertilizer plant based on Markov birth-death process using probabilistic approach. Ram and Singh (2009c) analyzed the reliability characteristics of a complex engineering system under copula by supplementary variable technique. Garg et al. (2010) described the availability of combed silver production system by supplementary variable technique of yarn production plant. Ahmad et al. (2011a) discussed the configurational modeling and stochastic analysis of a complex repairable industrial system model carried out by using regenerative point technique. Kumar and Lata (2011b) analyzed the reliability of piston manufacturing system by using the fault tree method. Khanduja et al. (2012) demonstrated the steady state behavior and maintenance planning of the bleaching system bases on Markov birth-death process using probabilistic approach of a paper plant. Suleiman et al. (2013a) introduced stochastic analysis and performance of complex thermal power plant by using probabilistic approach. Modgil et al. (2013b) discussed the performance model based on Markov birth-death process for shoe upper manufacturing unit and calculated the long term availability of the system. Aggarwal et al. (2017) analyzed the performance of butter oil production system using genetic algorithm. Pandey et al. (2018) discussed reliability analysis critical subsystem by risk priority numbers of the dragline. Kumari et al. (2019a) has been presented stochastic model of skimmed-milk producing system of the milk plant using supplementary variable technique. Kumari et al. (2019b) studied profit analysis of butter producing system by using supplementary variable technique of the milk plant. Mehta et al. (2019c) analyzed reliability of sheet manufacturing unit with supplementary variable technique of a steel industry. Gupta et al. (2020a) discussed behavioral analysis of cooling tower in steam turbine by using Markov birth-death process of the power plant. Saini et al. (2020b) presented availability and profit of coking system by using supplementary variable technique. Garg et al. (2020c) analyzed reliability of ammonia synthesis unit by using Markov birth-death process in a fertilizer plant. Aggarwal et al. (2021a) analyzed the profit of a standby repairable system with priority to preventive maintenance. Kumari et al. (2021b) discussed performance analysis of curd (Dahi) producing system of milk plant using trapezoidal fuzzy numbers with different left and right heights. Kumari et al. (2021c) evaluated profit analysis of skimmed milk powder producing system of milk plant using trapezoidal fuzzy numbers with different left and right heights.

Before, 19th century ingot casting method was used to solidify the molten steel in the history of the steel industry. This method was time consuming, costly and energy consuming etc. So, after the 19th century a new method is created to solidify the liquid steel called continuous casting method with more benefits such as better yield, save energy and manpower, improvement of steel quality.

In the world, fifty-five percentage of liquid steel production is solidified by continuous casting process in continuous casting system of steel industry. Continuous casting is the process whereby the liquid steel is solidified into semi finished products such as slabs, billets and blooms etc. This is the most important system in the production of steel in the whole steel industry. That's why there is need to study the behaviour of continuous casting system.

However, the authors/engineers Chakraborti et al. (2001), Marcial et al. (2003), Santos et al. (2005), Tavakoli (2018) and Shah (2019d) have been discussed the continuous casting mold using a pareto-converging genetic algorithm, modeling of the solidification process in a continuous casting installation for steel slabs, solidification mathematical model and a genetic algorithm in the optimization of strand thermal profile along the continuous casting of steel, the continuous casting process using distributed parameter identification approach-controlling the curvature of solid-liquid interface and optimized the continuous casting process in steel manufacturing industry respectively. The literature of continuous casting system revealed that the reliability measure of continuous casting system have not discussed by these researchers.

Therefore, the aim of the current study is to enhance the performance of continuous casting system of steel industry. Continuous casting system has six subsystems: “Pouring turret ladle”, “Tundish”, “Mold”, “Water spray chamber”, “Support roller” and “Torch cutter”. Series configuration is used to arrange these subsystems. The subsystem “Pouring turret ladle” is having three similar units. These units are operating in parallel. The subsystems “Tundish”, “Mold”, “Water spray chamber” and “Support roller” having single unit. The subsystem “Torch cutter” contains two identical units: one is operative and other keep in cold standby. For all subsystems, the distribution of repair rates and failure rates of continuous casting system are taken as arbitrary distributions. Analysis of continuous casting system has been done by using supplementary variable technique. The numerical results of reliability measure of continuous casting system in terms of availability and profit have been computed by assuming exponential, Rayleigh and Weibull distributions.

The paper has been organised into six sections. The present section comprises an introductory. Section 2 consists brief description of the system, assumptions, notations, and state-specification used in the system analysis. Mathematical modelling of the system has been carried out in Section 3. Section 4 concerns the profit analysis of the system. Numerical analysis of the continuous casting system is done by MATLAB in Section 5. Section 6 highlights the conclusion of the study.

2 System Description, Assumptions, Notations and State-specification

2.1 System Description

Pouring turret ladle (Subsystem A): – Subsystem “Pouring turret ladle” consists of three similar units are working in parallel. Pouring turret ladle is used to transfer the liquid steel. Failure of any one unit of subsystem A,

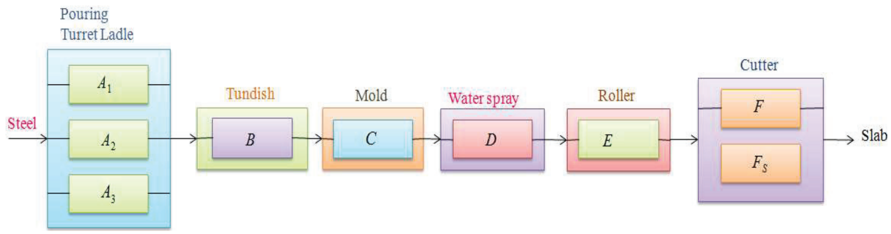

Figure 1 Process flow diagram of continuous casting system in steel industry.

continuous casting system works with reduce capacity. If any two units of subsystem A fail, then the system will completely fail.

Tundish (Subsystem B): – The Subsystem "Tundish" contain a single unit. The liquid steel which comes from Pouring turret ladle (Subsystem A) is transferred to Tundish via a pipe. Failure of this unit causes the system completely fails.

Mold (Subsystem C): – After Tundish (Subsystem B) liquid steel is pass through subsystem "Mold" (which contain cooled water) to solidify. Mold (subsystem C) has a single unit. This unit is fail then system is completely fails to work.

Water spray chamber (Subsystem D): – The subsystem "Water spray chamber" is having single unit. After Mold (subsystem C) the hot steel (strand) travels through water spray chamber which spray the water on it. Subsystem Water spray chamber fails to causes the system completely fails.

Support roller (Subsystem E): – The subsystem "Support roller" contains a single unit. After Water spray chamber (subsystem D) the strand passes through straightening rolls and withdrawal rolls to give pre-shapes of the final strand. System is fail completely when subsystem "Support roller" stops to perform its work.

Torch cutter (subsystem F): – The subsystem "Torch cutter" is having two units: one is operative and another keep in cold standby. After "Support roller" (Subsystem E) steel slab obtained from the strand cut into predetermined lengths by torch cutter. Both units fail to causes the system completely fails.

2.2 Assumptions

1. Initially, system is operative with full capacity.
2. Repairmen always available for the repair facility.
3. Repaired unit operative as a new unit.
4. Two units are not simultaneously failed.
5. The failure rates and repair rates of continuous casting system are considered as general distributions.

2.3 Notations

$A_i(i = 1, 2, 3), B, C, D, E, F, F_s$: System units working with full capacity. $i = 1, 2, 3$.

$\bar{A}_i(i = 1, 2, 3), \bar{B}, \bar{C}, \bar{D}, \bar{E}, \bar{F}, \bar{F}_s$: Failed units.

$\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5, \alpha_6$: Failure rates of $A_i(i = 1, 2, 3), B, C, D, E, F$ units respectively.

$\beta_1(x), \beta_2(x), \beta_3(x), \beta_4(x), \beta_5(x), \beta_6(x)$: Repair rates of $A_i(i=1, 2, 3)$, B, C, D, E, F units respectively.

$p_0(t)$: Probability that system is working at time t with full capacity of initially state 0.

$p_i(x, t)$ $i = 1, 2, \ldots, 23$: Probability that system is in state i at time t and have an elapsed repair time x.

L: Laplace Transformation.

$p_i(s)$ $i = 1, 2, \ldots, 23$: Laplace Transformation of all probabilities set.

2.4 State-specification

The states of the system are expressed as:

S_0: All subsystems of continuous casting system are good.
S_1: The operative unit of subsystem F is failed then the standby unit is in operative mode.
S_2: Any one unit of subsystem A is failed then system is operative in reduce capacity.
S_3: System operative in reduce capacity when any one unit of subsystem A is failed and operative unit of subsystem F is also failed and standby unit is in operative mode.
S_i: (i $= 4, 5, \ldots, 23$): Failure of any one subsystem causes the system completely failed due to series configuration.

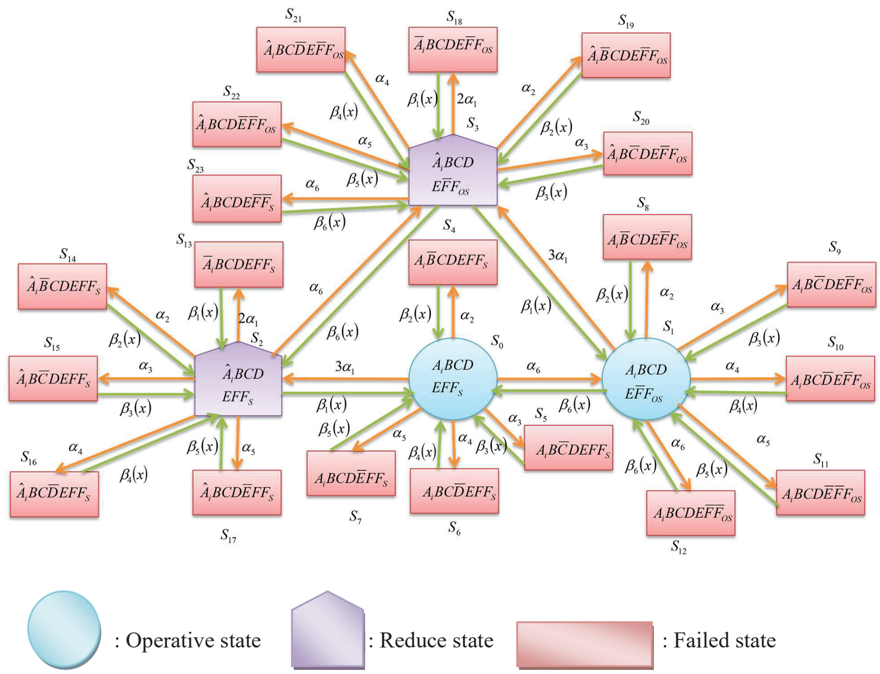

Figure 2 State-transition diagram of the continuous casting system.

3 Mathematical Modeling of the Continuous Casting System of the Steel Industry

The following difference-differential equations are associated with the model of continuous casting system is derived by using supplementary variable technique from the state transition diagram in Figure 2:

$$\left\{\frac{d}{dt} + 3\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \alpha_6\right\} p_0(t)$$
$$= \int_0^\infty \beta_1(x)p_2(x,t)dx + \int_0^\infty \beta_2(x)p_4(x,t)dx$$
$$+ \int_0^\infty \beta_3(x)p_5(x,t)dx + \int_0^\infty \beta_4(x)p_6(x,t)dx$$
$$+ \int_0^\infty \beta_5(x)p_7(x,t)dx + \int_0^\infty \beta_6(x)p_1(x,t)dx \qquad (1)$$

$$\left\{\frac{\partial}{\partial x}+\frac{\partial}{\partial t}+3\alpha_1+\alpha_2+\alpha_3+\alpha_4+\alpha_5+\alpha_6+\beta_6(x)\right\}p_1(x,t)$$
$$=\int_0^\infty \beta_1(x)p_3(x,t)dx+\int_0^\infty \beta_2(x)p_8(x,t)dx$$
$$+\int_0^\infty \beta_3(x)p_9(x,t)dx+\int_0^\infty \beta_4(x)p_{10}(x,t)dx$$
$$+\int_0^\infty \beta_5(x)p_{11}(x,t)dx+\int_0^\infty \beta_6(x)p_{12}(x,t)dx+\alpha_6p_0(t) \quad (2)$$

$$\left\{\frac{\partial}{\partial x}+\frac{\partial}{\partial t}+2\alpha_1+\alpha_2+\alpha_3+\alpha_4+\alpha_5+\alpha_6+\beta_1(x)\right\}p_2(x,t)$$
$$=\int_0^\infty \beta_1(x)p_{13}(x,t)dx+\int_0^\infty \beta_2(x)p_{14}(x,t)dx$$
$$+\int_0^\infty \beta_3(x)p_{15}(x,t)dx+\int_0^\infty \beta_4(x)p_{16}(x,t)dx$$
$$+\int_0^\infty \beta_5(x)p_{17}(x,t)dx+\int_0^\infty \beta_6(x)p_3(x,t)dx+3\alpha_1p_0(t) \quad (3)$$

$$\left\{\frac{\partial}{\partial x}+\frac{\partial}{\partial t}+2\alpha_1+\alpha_2+\alpha_3+\alpha_4+\alpha_5+\alpha_6+\beta_6(x)+\beta_1(x)\right\}p_3(x,t)$$
$$=\int_0^\infty \beta_1(x)p_{18}(x,t)dx+\int_0^\infty \beta_2(x)p_{19}(x,t)dx$$
$$+\int_0^\infty \beta_3(x)p_{20}(x,t)dx+\int_0^\infty \beta_4(x)p_{21}(x,t)dx$$
$$+\int_0^\infty \beta_5(x)p_{22}(x,t)dx+\int_0^\infty \beta_6(x)p_{23}(x,t)dx$$
$$+3\alpha_1p_1(x,t)+\alpha_6p_2(x,t) \quad (4)$$

$$\left\{\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\beta_2(x)\right\}p_4(x,t)=\alpha_2p_0(t) \quad (5)$$

$$\left\{\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\beta_3(x)\right\}p_5(x,t)=\alpha_3p_0(t) \quad (6)$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_4(x)\right\} p_6(x,t) = \alpha_4 p_0(t) \tag{7}$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_5(x)\right\} p_7(x,t) = \alpha_5 p_0(t) \tag{8}$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_2(x)\right\} p_8(x,t) = \alpha_2 p_1(x,t) \tag{9}$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_3(x)\right\} p_9(x,t) = \alpha_3 p_1(x,t) \tag{10}$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_4(x)\right\} p_{10}(x,t) = \alpha_4 p_1(x,t) \tag{11}$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_5(x)\right\} p_{11}(x,t) = \alpha_5 p_1(x,t) \tag{12}$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_6(x)\right\} p_{12}(x,t) = \alpha_6 p_1(x,t) \tag{13}$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_1(x)\right\} p_{13}(x,t) = 2\alpha_1 p_2(x,t) \tag{14}$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_2(x)\right\} p_{14}(x,t) = \alpha_2 p_2(x,t) \tag{15}$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_3(x)\right\} p_{15}(x,t) = \alpha_3 p_2(x,t) \tag{16}$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_4(x)\right\} p_{16}(x,t) = \alpha_4 p_2(x,t) \tag{17}$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_5(x)\right\} p_{17}(x,t) = \alpha_5 p_2(x,t) \tag{18}$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_1(x)\right\} p_{18}(x,t) = 2\alpha_1 p_3(x,t) \tag{19}$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_2(x)\right\} p_{19}(x,t) = \alpha_2 p_3(x,t) \tag{20}$$

$$\left\{\frac{\partial}{\partial t} + \frac{\partial}{\partial x} + \beta_3(x)\right\} p_{20}(x,t) = \alpha_3 p_3(x,t) \tag{21}$$

$$\left\{\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\beta_4(x)\right\}p_{21}(x,t)=\alpha_4 p_3(x,t) \tag{22}$$

$$\left\{\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\beta_5(x)\right\}p_{22}(x,t)=\alpha_5 p_3(x,t) \tag{23}$$

$$\left\{\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\beta_6(x)\right\}p_{23}(x,t)=\alpha_6 p_3(x,t) \tag{24}$$

Initial conditions

$$\left.\begin{array}{ll} p_0(0)=1, & \\ p_i=0, & i=1,2,3,\ldots,23 \end{array}\right\} \tag{25}$$

Boundary conditions

$$\left.\begin{array}{lll} p_1(0,t)=\alpha_6 p_0(t) & p_2(0,t)=3\alpha_1 p_0(t) & p_3(0,t)=3\alpha_1 p_1(t) \\ & & \quad +\alpha_6 p_2(t) \\ p_4(0,t)=\alpha_2 p_0(t) & p_5(0,t)=\alpha_3 p_0(t) & p_6(0,t)=\alpha_4 p_0(t) \\ p_7(0,t)=\alpha_5 p_0(t) & p_8(0,t)=\alpha_2 p_1(t) & p_9(0,t)=\alpha_3 p_1(t) \\ p_{10}(0,t)=\alpha_4 p_1(t) & p_{11}(0,t)=\alpha_5 p_1(t) & p_{12}(0,t)=\alpha_6 p_1(t) \\ p_{13}(0,t)=2\alpha_1 p_2(t) & p_{14}(0,t)=\alpha_2 p_2(t) & p_{15}(0,t)=\alpha_3 p_2(t) \\ p_{16}(0,t)=\alpha_4 p_2(t) & p_{17}(0,t)=\alpha_5 p_2(t) & p_{18}(0,t)=2\alpha_1 p_3(t) \\ p_{19}(0,t)=\alpha_2 p_3(t) & p_{20}(0,t)=\alpha_3 p_3(t) & p_{21}(0,t)=\alpha_4 p_3(t) \\ p_{22}(0,t)=\alpha_5 p_3(t) & p_{23}(0,t)=\alpha_6 p_3(t) & \end{array}\right\} \tag{26}$$

Equation (1) is first order linear differential equation while equations (2)–(24) are partial differential equations. The set of differential equations (1)–(24) together with the initial conditions (25) and boundary conditions (26) is called Chapman-Kolmogorov differential-difference equation. By using Laplace transformation from Equations (1)–(24) combined with the initial conditions (25) and boundary conditions (26) are used to obtain the reliability of continuous casting system of steel industry.

$$R(t)=L^{-1}(R(s))$$

$$R(s)=p_0(s)+p_1(s)+p_2(s)+p_3(s)$$

$$R(t)=\left\{\frac{\begin{matrix}1+\int_0^\infty \beta_1(x)p_1(x,s)dx+\int_0^\infty \beta_2(x)p_4(x,s)dx\\ +\int_0^\infty \beta_3(x)p_5(x,s)dx+\int_0^\infty \beta_4(x)p_6(x,s)dx\\ +\int_0^\infty \beta_5(x)p_7(x,s)dx+\int_0^\infty \beta_6(x)p_1(x,s)dx\end{matrix}}{\{s+3\alpha_1+\alpha_2+\alpha_3+\alpha_4+\alpha_5+\alpha_6\}}\right\}$$

$$+\int_0^\infty e^{-\int_0^\infty\begin{pmatrix}s+3\alpha_1+\alpha_2+\alpha_3+\alpha_4\\ +\alpha_5+\alpha_6+\beta_6(x)\end{pmatrix}dx}$$

$$\left[\int_0^\infty e^{\int_0^\infty\begin{pmatrix}s+3\alpha_1+\alpha_2+\alpha_3+\alpha_4\\ +\alpha_5+\alpha_6+\beta_6(x)\end{pmatrix}dx}\begin{matrix}\left\{\begin{matrix}\beta_1(x)p_3(x,s)+\beta_2(x)p_8(x,s)\\ +\beta_3(x)p_9(x,s)+\beta_4(x)p_{10}(x,s)\\ +\beta_5(x)p_{11}(x,s)+\beta_6(x)p_{12}(x,s)\end{matrix}\right\}\\ dx\\ +\alpha_6p_0(s)\left\{1+\int_0^\infty e^{\int_0^\infty\begin{pmatrix}s+3\alpha_1+\alpha_2\\ +\alpha_3+\alpha_4\\ +\alpha_5+\alpha_6\\ +\beta_6(x)\end{pmatrix}dx}dx\right\}\end{matrix}\right]dx$$

$$+\int_0^\infty e^{-\int_0^\infty\begin{pmatrix}s+2\alpha_1+\alpha_2+\alpha_3+\alpha_4\\ +\alpha_5+\alpha_6+\beta_1(x)\end{pmatrix}dx}$$

$$\left[\int_0^\infty e^{\int_0^\infty\begin{pmatrix}s+2\alpha_1+\alpha_2+\alpha_3+\alpha_4\\ +\alpha_5+\alpha_6+\beta_1(x)\end{pmatrix}dx}\begin{matrix}\left\{\begin{matrix}\beta_1(x)p_{13}(x,s)+\beta_2(x)p_{14}(x,s)\\ +\beta_3(x)p_{15}(x,s)+\beta_4(x)p_{16}(x,s)\\ +\beta_5(x)p_{17}(x,s)+\beta_6(x)p_3(x,s)\end{matrix}\right\}\\ dx\\ +3\alpha_1p_0(s)\left\{1+\int_0^\infty e^{\int_0^\infty\begin{pmatrix}s+2\alpha_1+\alpha_2\\ +\alpha_3+\alpha_4\\ +\alpha_5+\alpha_6\\ +\beta_1(x)\end{pmatrix}dx}dx\right\}\end{matrix}\right]dx$$

$$+\int_0^\infty e^{-\int_0^\infty \begin{pmatrix} s+2\alpha_1+\alpha_2+\alpha_3+\alpha_4 \\ +\alpha_5+\alpha_6+\beta_1(x)+\beta_6(x) \end{pmatrix} dx}$$

$$\left[\begin{array}{l} \begin{Bmatrix} \beta_1(x)p_{18}(x,s)+\beta_2(x)p_{19}(x,s) \\ +\beta_3(x)p_{20}(x,s)+\beta_4(x)p_{21}(x,s) \\ +\beta_5(x)p_{22}(x,s)+\beta_6(x)p_{23}(x,s) \end{Bmatrix} \\ e^{\int_0^\infty \begin{pmatrix} s+2\alpha_1+\alpha_2+\alpha_3+\alpha_4 \\ +\alpha_5+\alpha_6+\beta_1(x)+\beta_6(x) \end{pmatrix} dx} dx \\ \int_0^\infty \\ \quad +\{3\alpha_1 p_1(s)+\alpha_6 p_2(s)\} \left\{\begin{array}{l} e^{\int_0^\infty \begin{pmatrix} s+2\alpha_1+\alpha_2 \\ +\alpha_3+\alpha_4 \\ +\alpha_5+\alpha_6 \\ +\beta_1(x) \\ +\beta_6(x) \end{pmatrix} dx} \\ +1-\int_0^\infty \\ e^{\int_0^\infty \begin{pmatrix} s+2\alpha_1+\alpha_2 \\ +\alpha_3+\alpha_4 \\ +\alpha_5+\alpha_6 \\ +\beta_1(x) \\ +\beta_6(x) \end{pmatrix} dx} \\ \begin{pmatrix} s+2\alpha_1+\alpha_2 \\ +\alpha_3+\alpha_4 \\ +\alpha_5+\alpha_6 \\ +\beta_1(x)+\beta_6(x) \end{pmatrix} dx \end{array}\right\} dx \end{array}\right] \tag{27}$$

3.1 Particular Case

The Weibull density function for two parameters is given by:

$$f_i(t) = K\alpha_i(\alpha_i t)^{K-1}\exp[-(\alpha_i t)^K], \quad t \geq 0, \alpha > 0$$

$$g_i(t) = K\beta_i(\beta_i t)^{K-1}\exp[-(\beta_i t)^K]; \quad t \geq 0, \beta > 0$$

Where $i = 1, 2, \ldots 6$.

Here, K is shape parameter, α, β are scale parameters. If $K = 1$, it reduce in exponential distribution and it become Rayleigh distribution if $K > 1$. For analysis the performance of continuous casting system by considering repair rates as exponentially distributed. Then, the difference differential Equations (1)–(24) are associated with the continuous casting system model is given below:

$$\left[\frac{d}{dt} + 3\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \alpha_6\right] p_0(t)$$
$$= \beta_1 p_2(t) + \beta_2 p_4(t) + \beta_3 p_5(t) + \beta_4 p_6(t) + \beta_5 p_7(t) + \beta_6 p_1(t) \tag{28}$$

$$\left[\frac{d}{dt} + 3\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \alpha_6 + \beta_6\right] p_1(t)$$
$$= \beta_1 p_3(t) + \beta_2 p_8(t) + \beta_3 p_9(t) + \beta_4 p_{10}(t) + \beta_5 p_{11}(t) + \beta_6 p_{12}(t) + \alpha_6 p_0(t) \tag{29}$$

$$\left[\frac{d}{dt} + 2\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \alpha_6 + \beta_1\right] p_2(t)$$
$$= \beta_1 p_{13}(t) + \beta_2 p_{14}(t) + \beta_3 p_{15}(t) + \beta_4 p_{16}(t) + \beta_5 p_{17}(t) + \beta_6 p_3(t) + 3\alpha_1 p_0(t) \tag{30}$$

$$\left[\frac{d}{dt} + 2\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \alpha_6 + \beta_1 + \beta_6\right] p_3(t)$$
$$= \beta_1 p_{18}(t) + \beta_2 p_{19}(t) + \beta_3 p_{20}(t) + \beta_4 p_{21}(t) + \beta_5 p_{22}(t) + \beta_6 p_{23}(t) + 3\alpha_1 p_1 + \alpha_6 p_2(t) \tag{31}$$

$$\left[\frac{d}{dt} + \beta_2\right] p_4(t) = \alpha_2 p_0(t) \tag{32}$$

$$\left[\frac{d}{dt} + \beta_3\right] p_5(t) = \alpha_3 p_0(t) \tag{33}$$

$$\left[\frac{d}{dt} + \beta_4\right] p_6(t) = \alpha_4 p_0(t) \tag{34}$$

$$\left[\frac{d}{dt}+\beta_5\right]p_7(t)=\alpha_5 p_0(t) \tag{35}$$

$$\left[\frac{d}{dt}+\beta_2\right]p_8(t)=\alpha_2 p_1(t) \tag{36}$$

$$\left[\frac{d}{dt}+\beta_3\right]p_9(t)=\alpha_3 p_1(t) \tag{37}$$

$$\left[\frac{d}{dt}+\beta_4\right]p_{10}(t)=\alpha_4 p_1(t) \tag{38}$$

$$\left[\frac{d}{dt}+\beta_5\right]p_{11}(t)=\alpha_5 p_1(t) \tag{39}$$

$$\left[\frac{d}{dt}+\beta_6\right]p_{12}(t)=\alpha_6 p_1(t) \tag{40}$$

$$\left[\frac{d}{dt}+\beta_1\right]p_{13}(t)=2\alpha_1 p_2(t) \tag{41}$$

$$\left[\frac{d}{dt}+\beta_2\right]p_{14}(t)=\alpha_2 p_2(t) \tag{42}$$

$$\left[\frac{d}{dt}+\beta_3\right]p_{15}(t)=\alpha_3 p_2(t) \tag{43}$$

$$\left[\frac{d}{dt}+\beta_4\right]p_{16}(t)=\alpha_4 p_2(t) \tag{44}$$

$$\left[\frac{d}{dt}+\beta_5\right]p_{17}(t)=\alpha_5 p_2(t) \tag{45}$$

$$\left[\frac{d}{dt}+\beta_1\right]p_{18}(t)=2\alpha_1 p_3(t) \tag{46}$$

$$\left[\frac{d}{dt}+\beta_2\right]p_{19}(t)=\alpha_2 p_3(t) \tag{47}$$

$$\left[\frac{d}{dt}+\beta_3\right]p_{20}(t)=\alpha_3 p_3(t) \tag{48}$$

$$\left[\frac{d}{dt}+\beta_4\right]p_{21}(t)=\alpha_4 p_3(t) \tag{49}$$

$$\left[\frac{d}{dt} + \beta_5\right] p_{22}(t) = \alpha_5 p_3(t) \tag{50}$$

$$\left[\frac{d}{dt} + \beta_6\right] p_{23}(t) = \alpha_6 p_3(t) \tag{51}$$

Initial conditions

$$p_0(0) = 1$$
$$p_i(0) = 0, \quad 1 \le i \le 23$$

The set of steady state probabilities are achieved by taking $\frac{d}{dt} = 0; t \to \infty$ and $p_i(t) = p_i$ in Equations (28)–(51).

$$p_1 = Dp_0 \quad p_2 = Ep_0 \quad p_3 = Fp_0$$

Here

$$D = \frac{(\alpha_6 + 3\alpha_1)\{(\alpha_6 + \beta_1)(\beta_1 + \beta_6) - \alpha_2\} - 3\alpha_1\beta_1(\beta_1 + \beta_6)}{3\alpha_1\beta_1\beta_6}$$

$$E = \frac{3\alpha_1\{(1 + D)\beta_6 + \beta_1\}}{(\alpha_6 + \beta_1)(\beta_1 + \beta_6) - \alpha_6} \quad F = \frac{3\alpha_1 D + \alpha_6 E}{\beta_1 + \beta_6}$$

By using the normalizing condition $\sum p_i = 1$ we obtain

$$p_0 = \left[\begin{array}{l} \left(1 + D + E + F + \frac{\alpha_2}{\beta_2} + \frac{\alpha_3}{\beta_3} + \frac{\alpha_4}{\beta_4} + \frac{\alpha_5}{\beta_5}\right) \\ \quad + \left(\frac{\alpha_2}{\beta_2} + \frac{\alpha_3}{\beta_3} + \frac{\alpha_4}{\beta_4} + \frac{\alpha_5}{\beta_5} + \frac{\alpha_6}{\beta_6}\right) D \\ \quad + \left(\frac{2\alpha_1}{\beta_1} + \frac{\alpha_2}{\beta_2} + \frac{\alpha_3}{\beta_3} + \frac{\alpha_4}{\beta_4} + \frac{\alpha_5}{\beta_5}\right) E \\ \quad + \left(\frac{2\alpha_1}{\beta_1} + \frac{\alpha_2}{\beta_2} + \frac{\alpha_3}{\beta_3} + \frac{\alpha_4}{\beta_4} + \frac{\alpha_5}{\beta_5} + \frac{\alpha_6}{\beta_6}\right) F \end{array}\right]^{-1} \tag{52}$$

Now, the Availability of system is:

$$A_v = p_0 + p_1 + p_2 + p_3$$
$$A_v = p_0 + Dp_0 + Ep_0 + Fp_0$$
$$A_v = (1 + D + E + F)p_0 \tag{53}$$

4 Profit Analysis

The net profit of continuous casting system is derived by using Equation (53):

Profit $= TA_v - C$
Profit $= T\{(1 + D + E + F)p_0 - C\}$
$A_v =$ Steady state availability of the continuous casting system.
T = Total revenue per unit up time of the continuous casting system.
C = Total repair cost of the continuous casting system.

5 Numerical Analysis

To show the behavior of the continuous casting system, availability and profit analysis has been done by assuming exponential, Rayleigh and Weibull distributions.

Table 1 For Exponential distribution, failure rates impact on availability of subsystems of continuous casting system of steel industry

	Availability						
	$\beta_1 = 0.1, \beta_2 = 0.15, \beta_3 = 0.2, \beta_4 = 0.25, \beta_5 = 0.2, \beta_6 = 0.15$						
Time (In months) ↓	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.02$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.025$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.03$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.035$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.04$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.045$
2	0.8541	0.8515	0.839	0.8395	0.8411	0.8439	0.8533
4	0.7577	0.7506	0.7349	0.736	0.7388	0.7424	0.7556
6	0.6942	0.6822	0.6676	0.6693	0.6729	0.6767	0.6906
8	0.6525	0.6362	0.624	0.6264	0.6304	0.6341	0.6477
10	0.6247	0.6052	0.5957	0.5986	0.6031	0.6064	0.6191
12	0.6064	0.584	0.5772	0.5806	0.5851	0.5882	0.6001
14	0.5938	0.5692	0.5649	0.5687	0.5733	0.576	0.587
16	0.5854	0.5588	0.5566	0.5607	0.5653	0.5679	0.5781
18	0.5793	0.5513	0.5511	0.5551	0.5599	0.5622	0.5719
20	0.575	0.5457	0.5455	0.5514	0.5559	0.5583	0.5674

Table 2 For Exponential distribution, failure rates impact on profit of subsystems of continuous casting system of steel industry

	Profit						
	$\beta_1 = 0.1, \beta_2 = 0.15, \beta_3 = 0.2, \beta_4 = 0.25, \beta_5 = 0.2, \beta_6 = 0.15$						
Time (In months) ↓	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.02$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.025$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.03$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.035$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.04$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.045$
2	3770.5	3757.5	3695	3697.5	3705.5	3719.5	3766.5
4	3288.5	3253	3174.5	3180	3194	3212	3278
6	2971	2911	2838	2846.5	2864.5	2883.5	2953
8	2762.5	2681	2620	2632	2652	2670.5	2738.5
10	2623.5	2526	2478.5	2493	2515.5	2532	2595.5
12	2532	2420	2386	2403	2425.5	2441	2500.5
14	2469	2346	2324.5	2343.5	2366.5	2380	2435
16	2427	2294	2283	2303.5	2326.5	2339.5	2390.5
18	2396.5	2256.5	2255.5	2275.5	2299.5	2311	2359.5
20	2375	2228.5	2227.5	2257	2279.5	2291.5	2337

Table 3 For Exponential distribution, repair rates impact on availability of subsystems of the continuous casting system of steel industry

	Availability						
	$\alpha_1 = 0.01, \alpha_2 = 0.02, \alpha_3 = 0.015, \alpha_4 = 0.02, \alpha_5 = 0.025, \alpha_6 = 0.03$						
Time (In months) ↓	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.2$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.25$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.3$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.3$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.35$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.4$
2	0.8691	0.8693	0.8705	0.8699	0.8701	0.87	0.8693
4	0.7811	0.7814	0.7848	0.7832	0.7839	0.7833	0.7811
6	0.722	0.7228	0.7286	0.7255	0.7267	0.7258	0.7222
8	0.6823	0.6839	0.6915	0.6872	0.6887	0.6875	0.6829
10	0.6558	0.6581	0.6671	0.6615	0.6635	0.6618	0.6565
12	0.638	0.641	0.6511	0.6443	0.6464	0.6445	0.6387
14	0.6258	0.6296	0.6402	0.6327	0.635	0.6327	0.6267
16	0.6175	0.622	0.6328	0.6246	0.6272	0.6247	0.6185
18	0.6116	0.6169	0.6277	0.6191	0.6216	0.619	0.6126
20	0.6079	0.6135	0.6241	0.6151	0.6176	0.6149	0.6087

Table 4 For Exponential distribution, repair rates impact on profit of subsystems of the continuous casting system of steel industry

Profit							
$\alpha_1 = 0.01, \alpha_2 = 0.02, \alpha_3 = 0.015, \alpha_4 = 0.02, \alpha_5 = 0.025, \alpha_6 = 0.03$							
Time (In months) ↓	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.2$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.25$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.3$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.3$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.35$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.4$
2	3845.5	3846.5	3852.5	3849.5	3850.5	3850	3846.5
4	3405.5	3407	3424	3416	3419.5	3416.5	3405.5
6	3110	3114	3143	3127.5	3133.5	3129	3111
8	2911.5	2919.5	2957.5	2936	2943.5	2937.5	2914.5
10	2779	2790.5	2835.5	2807.5	2817.5	2809	2782.5
12	2690	2705	2755.5	2721.5	2732	2722.5	2693.5
14	2629	2648	2701	2663.5	2675	2663.5	2633.5
16	2587.5	2610	2664	2623	2636	2623.5	2592.5
18	2558	2584.5	2638.5	2595.5	2608	2595	2563
20	2539.5	2567.5	2620.5	2575.5	2588	2574.5	2543.5

Table 5 For Rayleigh distribution, failure rates impact on availability of subsystems of the continuous casting system of steel industry

Availability							
$\beta_1 = 0.1, \beta_2 = 0.15, \beta_3 = 0.2, \beta_4 = 0.25, \beta_5 = 0.2, \beta_6 = 0.15$							
Time (In months) ↓	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.02$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.025$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.03$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.035$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.04$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.045$
2	0.8573	0.8548	0.8427	0.8431	0.8435	0.8431	0.8562
4	0.7694	0.7623	0.7475	0.7489	0.7498	0.7489	0.7675
6	0.7153	0.7035	0.6898	0.6921	0.6935	0.6921	0.7107
8	0.6861	0.666	0.6546	0.6577	0.6597	0.6577	0.6758
10	0.6606	0.6416	0.633	0.6367	0.639	0.6367	0.6538
12	0.6471	0.6255	0.6194	0.6236	0.6261	0.6236	0.6396
14	0.6384	0.6143	0.6092	0.6152	0.6179	0.6098	0.6304
16	0.6325	0.6067	0.6051	0.6098	0.6124	0.6098	0.624
18	0.6284	0.6009	0.6007	0.606	0.6088	0.606	0.6196
20	0.6256	0.5965	0.5960	0.6035	0.6061	0.6035	0.6164

Table 6 For Rayleigh distribution, failure rates impact on profit of subsystems of the continuous casting system of steel industry

Profit							
$\beta_1 = 0.1, \beta_2 = 0.15, \beta_3 = 0.2, \beta_4 = 0.25, \beta_5 = 0.2, \beta_6 = 0.15$							
Time (In months) ↓	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.02$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.025$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.03$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.035$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.04$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.045$
2	3786.5	3774	3713.5	3715.5	3717.5	3715.5	3781
4	3347	3311.5	3237.5	3244.5	3249	3244.5	3337.5
6	3076.5	3017.5	2949	2960.5	2967.5	2960.5	3053.5
8	2930.5	2830	2773	2788.5	2798.5	2788.5	2879
10	2803	2708	2665	2683.5	2695	2683.5	2769
12	2735.5	2627.5	2597	2618	2630.5	2618	2698
14	2692	2571.5	2546	2576	2589.5	2549	2652
16	2662.5	2533.5	2525.5	2549	2562	2549	2620
18	2642	2504.5	2503.5	2530	2544	2530	2598
20	2628	2482.5	2480	2517.5	2530.5	2517.5	2582

Table 7 For Rayleigh distribution, repair rates impact on availability of subsystems of the continuous casting system of steel industry

Availability							
$\alpha_1 = 0.01, \alpha_2 = 0.02, \alpha_3 = 0.015, \alpha_4 = 0.02, \alpha_5 = 0.025, \alpha_6 = 0.03$							
Time (In months) ↓	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.2$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.25$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.3$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.3$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.35$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.4$
2	0.872	0.8721	0.8737	0.8729	0.8731	0.8726	0.872
4	0.7918	0.7922	0.7967	0.7941	0.7954	0.7936	0.7918
6	0.7415	0.7426	0.7499	0.7454	0.7466	0.74455	0.7416
8	0.71	0.7119	0.7212	0.715	0.7167	0.7138	0.7101
10	0.6901	0.693	0.7035	0.6958	0.6979	0.6944	0.6902
12	0.6774	0.6812	0.6924	0.6838	0.6859	0.682	0.6774
14	0.669	0.6737	0.6853	0.6757	0.678	0.6738	0.6692
16	0.6635	0.669	0.6807	0.6704	0.6729	0.6685	0.6637
18	0.6598	0.666	0.6775	0.6668	0.6692	0.6647	0.6599
20	0.6571	0.664	0.6752	0.6642	0.6666	0.6621	0.6573

Table 8 For Rayleigh distribution, repair rates impact on profit of subsystems of the continuous casting system of steel industry

Profit							
	$\alpha_1 = 0.01, \alpha_2 = 0.02, \alpha_3 = 0.015, \alpha_4 = 0.02, \alpha_5 = 0.025, \alpha_6 = 0.03$						
Time (In months) ↓	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.2$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.25$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.3$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.3$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.35$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.4$
2	3860	3860.5	3868.5	3864.5	3865.5	3863	3860
4	3459	3461	3483.5	3470.5	3477	3468	3459
6	3207.5	3213	3249.5	3227	3233	3222.75	3208
8	3050	3059.5	3106	3075	3083.5	3069	3050.5
10	2950.5	2965	3017.5	2979	2989.5	2972	2951
12	2887	2906	2962	2919	2929.5	2910	2887
14	2845	2868.5	2926.5	2878.5	2890	2869	2846
16	2817.5	2845	2903.5	2852	2864.5	2842.5	2818.5
18	2799	2830	2887.5	2834	2846	2823.5	2799.5
20	2785.5	2820	2876	2821	2833	2810.5	2786.5

Table 9 For Weibull distribution, failure rates impact on availability of subsystems of the continuous casting system of steel industry

Availability							
	$\beta_1 = 0.1, \beta_2 = 0.15, \beta_3 = 0.2, \beta_4 = 0.25, \beta_5 = 0.2, \beta_6 = 0.15$						
Time (In months) ↓	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.02$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.025$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.03$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.035$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.04$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.045$
2	0.8764	0.8746	0.8647	0.8654	0.8659	0.8661	0.8759
4	0.7876	0.7823	0.7689	0.7632	0.7714	0.7716	0.7861
6	0.7241	0.7148	0.7011	0.7033	0.7049	0.7047	0.7212
8	0.6785	0.6656	0.6533	0.656	0.658	0.6575	0.6744
10	0.6457	0.6297	0.6194	0.6228	0.627	0.6243	0.6409
12	0.6221	0.6034	0.5954	0.5991	0.6018	0.6007	0.6168
14	0.6052	0.5858	0.5783	0.5824	0.5852	0.584	0.5991
16	0.5928	0.5697	0.566	0.5704	0.5734	0.5719	0.5862
18	0.5836	0.559	0.5571	0.5616	0.5647	0.5631	0.5767
20	0.5769	0.5499	0.5495	0.5553	0.5585	0.5567	0.5697

Table 10 For Weibull distribution, failure rates impact on profit of subsystems of the continuous casting system of steel industry

Profit							
$\beta_1 = 0.1, \beta_2 = 0.15, \beta_3 = 0.2, \beta_4 = 0.25, \beta_5 = 0.2, \beta_6 = 0.15$							
Time (In months) ↓	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.02$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.025$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.03$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.035$ $\alpha_5 = 0.03$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.04$ $\alpha_6 = 0.035$	$\alpha_1 = 0.01$ $\alpha_2 = 0.015$ $\alpha_3 = 0.02$ $\alpha_4 = 0.025$ $\alpha_5 = 0.03$ $\alpha_6 = 0.045$
2	3882	3873	3823.5	3827	3829.5	3830.5	3879.5
4	3438	3411.5	3344.5	3316	3357	3358	3430.5
6	3120.5	3074	3005.5	3016.5	3024.5	3023.5	3106
8	2892.5	2828	2766.5	2780	2790	2787.5	2872
10	2728.5	2648.5	2597	2614	2635	2621.5	2704.5
12	2610.5	2517	2477	2495.5	2509	2503.5	2584
14	2526	2429	2391.5	2412	2426	2420	2495.5
16	2464	2348.5	2330	2352	2367	2359.5	2431
18	2418	2295	2285.5	2308	2323.5	2315.5	2383.5
20	2384.5	2249.5	2247.5	2276.5	2292.5	2283.5	2348.5

Table 11 For Weibull distribution, repair rates impact on availability of subsystems of the continuous casting system of steel industry

Availability							
$\alpha_1 = 0.01, \alpha_2 = 0.02, \alpha_3 = 0.015, \alpha_4 = 0.02, \alpha_5 = 0.025, \alpha_6 = 0.03$							
Time (In months) ↓	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.2$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.25$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.3$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.3$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.35$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.4$
2	0.8877	0.8879	0.8887	0.8884	0.8886	0.8887	0.8878
4	0.8061	0.8065	0.8092	0.8081	0.8087	0.809	0.8062
6	0.747	0.7477	0.7524	0.7504	0.7515	0.7517	0.7474
8	0.7042	0.7053	0.7122	0.7091	0.7107	0.7108	0.7048
10	0.6732	0.675	0.6834	0.6794	0.6813	0.6813	0.6741
12	0.6507	0.6532	0.6627	0.658	0.6601	0.66	0.6517
14	0.6344	0.6375	0.6481	0.6423	0.6448	0.6444	0.6355
16	0.6223	0.6263	0.6373	0.6309	0.6337	0.633	0.6238
18	0.6135	0.6182	0.6296	0.6226	0.6253	0.6247	0.615
20	0.6069	0.6123	0.6239	0.6163	0.6192	0.6182	0.6086

Table 12 For Weibull distribution, repair rates impact on profit of subsystems of the continuous casting system of steel industry

	Profit						
	$\alpha_1 = 0.01, \alpha_2 = 0.02, \alpha_3 = 0.015, \alpha_4 = 0.02, \alpha_5 = 0.025, \alpha_6 = 0.03$						
Time (In months) ↓	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.2$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.25$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.3$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.3$ $\beta_5 = 0.25$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.35$ $\beta_6 = 0.3$	$\beta_1 = 0.1$ $\beta_2 = 0.15$ $\beta_3 = 0.2$ $\beta_4 = 0.2$ $\beta_5 = 0.25$ $\beta_6 = 0.4$
2	3938.5	3939.5	3943.5	3942	3943	3943.5	3939
4	3530.5	3532.5	3546	3540.5	3543.5	3545	3531
6	3235	3238.5	3262	3252	3257.5	3258.5	3237
8	3021	3026.5	3061	3045.5	3053.5	3054	3024
10	2866	2875	2917	2897	2906.5	2906.5	2870.5
12	2753.5	2766	2813.5	2790	2800.5	2800	2758.5
14	2672	2687.5	2740.5	2711.5	2724	2722	2677.5
16	2611.5	2631.5	2686.5	2654.5	2668.5	2665	2619
18	2567.5	2591	2648	2613	2626.5	2623.5	2575
20	2534.5	2561.5	2619.5	2581.5	2596	2591	2543

Table 13 Impact of failure rates on availability of the continuous casting system follows Exponential, Rayleigh and Weibull distributions

Time (In months) ↓	Expoenetial Distribution	Rayleigh Distribution	Weibull Distribution
2	0.8541	0.8573	0.8764
4	0.7577	0.7694	0.7876
6	0.6942	0.7153	0.7241
8	0.6525	0.6861	0.6785
10	0.6247	0.6606	0.6457
12	0.6064	0.6471	0.6221
14	0.5938	0.6384	0.6052
16	0.5854	0.6325	0.5928
18	0.5793	0.6284	0.5836
20	0.575	0.6256	0.5769

Table 14 Impact of failure rates on profit of continuous casting system follows Exponential, Rayleigh and Weibull distributions

Time (In months) ↓	Expoenetial Distribution	Rayleigh Distribution	Weibull Distribution
2	3770.5	3786.5	3882
4	3288.5	3347	3438
6	2971	3076.5	3120.5
8	2762.5	2930.5	2892.5
10	2623.5	2803	2728.5
12	2532	2735.5	2610.5
14	2469	2692	2526
16	2427	2662.5	2464
18	2396.5	2642	2418
20	2375	2628	2384.5

Table 15 Impact of repair rates on availability of the continuous casting system follows Exponential, Rayleigh and Weibull distributions

Time (In months) ↓	Expoenetial Distribution	Rayleigh Distribution	Weibull Distribution
2	0.8691	0.872	0.8877
4	0.7811	0.7918	0.8061
6	0.722	0.7415	0.747
8	0.6823	0.71	0.7042
10	0.6558	0.6901	0.6732
12	0.638	0.6774	0.6507
14	0.6258	0.669	0.6344
16	0.6175	0.6635	0.6223
18	0.6116	0.6598	0.6135
20	0.6079	0.6571	0.6069

Table 16 Impact of repair rates on profit of the continuous casting system follows Exponential, Rayleigh and Weibull distributions

Time (In months) ↓	Expoenetial Distribution	Rayleigh Distribution	Weibull Distribution
2	3845.5	3860	3938.5
4	3405.5	3459	3530.5
6	3110	3207.5	3235
8	2911.5	3050	3021
10	2779	2950.5	2866
12	2690	2887	2753.5
14	2629	2845	2672
16	2587.5	2817.5	2611.5
18	2558	2799	2567.5
20	2539.5	2785.5	2534.5

6 Conclusion

Effect of failure rates and repair rates of the subsystems of continuous casting system namely: “Pouring turret ladle”, “Tundish”, “Mold”, “Water spray chamber”, “Support roller” and “Torch cutter” on availability and profit are expressed in Tables 1–16 for different parametric values of exponential, Rayleigh and Weibull distributions.

To see the impact of failure rate, the availability and profit of continuous casting system for exponential, Rayleigh and Weibull distributions are presented with in Tables 1&2, 5&6 and 9&10 respectively. These tables reflect that the availability and profit of continuous casting system steadily in reducing pattern with increases in the failure rates of subsystems $A_i(i = 1, 2, 3), B, C, D, E, F$. However, it is observed/found that “Tundish” i.e. subsystem B has more significantly impact of failure rates of the continuous casting system as compare to other subsystems such as “Pouring turret ladle”, “Mold”, “Water spray chamber”, “Support Roller” and “Torch Cutter”.

The numerical results of the availability and profit of the continuous casting system for repair rates are presented in Tables 3&4, 7&8 and 11&12 for exponential, Rayleigh and Weibull distributions respectively. From these tables, it has been identified that the availability and profit of continuous casting system keep on increasing with increase in the repair rates of subsystems $A_i(i = 1, 2, 3), B, C, D, E, F$. Also, it is examined that the subsystem "Tundish" i.e. subsystem B has significant effect of repair rates on availability and profit of the continuous casting system as compare to other subsystems "Pouring turret ladle", "Mold", "Water spray chamber", "Support roller" and "Torch cutter".

Also, the numerical analysis of availability and profit of continuous casting system are obtained for exponential, Rayleigh and Weibull distributions with respect to time in Tables 13–16 respectively. From these tables, it is observed that as time increasing, availability and profit both are decreasing. Also, numerical values for availability and profit of continuous casting system are more for Weibull distribution if $t < 8$ and for Rayleigh distribution if $t \geq 8$.

The aim of the present paper is to identify the most sensitive subsystem of continuous casting system. By controlling the failure rate of the most sensitive subsystem, the performance of continuous casting system can be enhanced. By increasing the repair rate of sensitive subsystem the availability and profit of the steel industry can also enhance. The availability and profit analysis of steel industrial systems can help the management of steel industry in taking timely decision for its smooth functioning and will help to reduce the costs of production

The above numerical interpretation of effect of failure rates and repair rates on overall availability and profit of continuous casting system, it has been concluded that to optimized (availability & profit) the performance of the continuous casting system of the steel industry, there is need to control the failure rate of subsystem "Tundish" i.e. subsystem B. In addition, if random variables of continuous casting system are associated with Weibull distribution if $t < 8$ and for Rayleigh distribution if $t \geq 8$, continuous casting system can be made more availability for utilizing and profitable.

Limitation

Some more distributions can be used for the analysis purpose.

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