Mathematical Modeling and Time Dependent Availability Analysis of Poly - Ethylene Terephthalate Bottle Hot Drink Filling System: A Case Study

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Article History Received: 10 January 2021; Revised: 12 February 2021; Accepted: 27 March 2021; Published online: 28 April 2021

Abstract: The current research aims to analyze the Time Dependent System Availability (TDSA) and identify the most sensitive component/unit of Poly Ethylene Terephthalate (PET) Bottle Hot Drink Filling System of a beverage Industry with Markovian approach. TDSA and Mean time between failures (MTBF) is computed for system concerned. The industrial system chosen includes five components namely Blow Moulding Machine, Filling Machine, Cooling Machine, Labeling Machine and Coding Machine. Transition diagram of the system has been developed and respective Chapman-Kolmogorov equations are originated. The derived equations are further simplified by an advance and receptive method acknowledged as adjustive step size control Runge-Kutta method. On basis of TDSA analysis most sensitive unit/component has been identified and maintenance priorities to other units/components have been assigned.

Keywords: Markov Process, TDSA, Runge-Kutta, MTBF.

1. Introduction

With the advancement in the field of automation industries are becoming complicated and determining their failure-free operation is very difficult. So, availability of an industrial system is very essential to meet the production goal. The overall availability of the system depends on the individual component performance. Thus, it assists in recognizing all potential design improvements. These alterations are essential to enhance the performance, MTBF and availability of the unit. In present research work the TDSA analysis and prioritize the maintenance activities are determined using MARKOV modeling method. Several researchers have contributed in the field of availability analysis using Markov technique and other methods, Since last few decades. Okafor et al.[1], Kumar and Tewari, [2], Gupta and Tewari [4], Kumar [3], N. Tomsaz et al. [5], and Gupta et al.[6] applied Markov method to make system transition diagram and assess its performance. Singh & Dayal (9) explained 1 out of N: G system with common cause failure. Singh I.P. [8] considered the performance analysis of a system having four types of machinery with pre-emptive priority repairs. Singh and Dayal [7] also discussed the reliability analysis of a repairable system in a changeable atmosphere. Sharma and Modgil [10] developed Mathematical model for leaf spring making unit. Wang et al. [11] discussed the performance of power system helps to select the redundancy in case of equipment failure. it is necessary to identify the critical component/subsystem and assigning repair/maintenance priority for all the subsystem of the system composed off.

In the present case, a mathematical model of Poly Ethylene Terephthalate (PET) Bottle Hot Drink Filling System of beverage industry has been determined using probabilistic approach. After solving the mathematical model using adaptive step size control Runge Kutta method TDSA analysis has been carried out to access the effect of time on system availability. On the basis of TDSA analysis MTBF of the system concerned has been calculated by Simpson $1/3^{rd}$ rule. Further on the basis of effect of repair rates on the system availability of system maintenance repair activities has been prioritized.

2. System Description

The Process flow chart of PET Bottle Hot Drink Bottling System of beverage industry is shown in figure No. 1. It comprises of five subsystems as discussed below:

Blow Moulding Machine (A): It is used to make the PET bottle from raw material i.e Preform by blow moulding operation of various capacities. These are two in numbers and subjected to major and minor failure.

Filling Machine (B): The filling machine cleans the bottle first, then fill the metered quantity of hot drink i.e. at a temperature of 70^0C, after that capping operation is performed with sealing. This machine is subjected to major failure.

Cooling Machine(C): It brings down the temperature of filled bottle from 70^0C to room temperature by sprinkling cooling water on the bottle.

Coding Machine (D): It is used to print all the material about price, batch number, date of manufacturing etc. on the filled bottle. This machine is subjected to major failure only.

Labeling Machine (E): The labeling machine is used to paste the label on filled bottle. This is also one number and subjected to minor as well as major failure.

Pasteurizer cum Storage Tank: This subsystem is used to store and heat the mango pulp upto 70^0C. This pulp is than feed to the filling machine. This subsystem is subjected to minor failure only, hence not being considered for analysis.

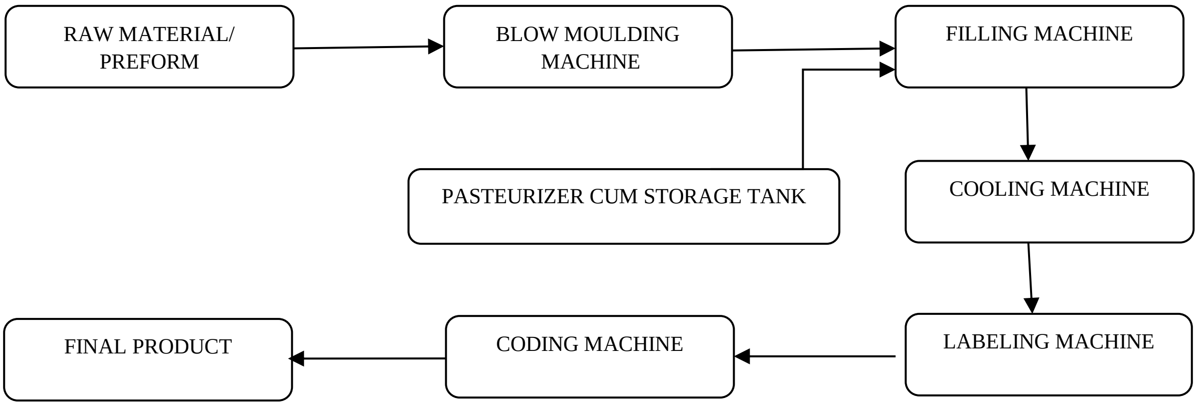

Figure 1. Flow Chart of PET Bottle Hot Drink Bottling System

Assumptions

1. All the component/Machines are in active state initially.
2. Each component/Machine is as upright as new after repair.
3. Failure and repair parameters of the component/Machine are constant.
4. The repair begins instantly after a component/Machine fails.

Notations

A : Blow Moulding Machines. (2Nos.)
B : Filling Machine (1No.)
C : Cooling Machine (1No.)
D : Labeling Machine (1No.)
E : Coding Machine (1No.)
$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$: Failure rate of A,B,C,D,E.
$\mu_1, \mu_2, \mu_3, \mu_4, \mu_5$: Repair rate of A, B,C,D,E.
λ_6, μ_6 : Failure & Repair rate of A in reduced state.
$P_i(t)$: Probability at time 't' and the system is in i^{th} state.
A(t) : Time Dependent System Availability
$A(\infty)$: Long Run Availability

Above mentioned assumptions, notations are considered for developing the transition diagram of the PET bottle hot drink filling system as shown in figure no. 2.

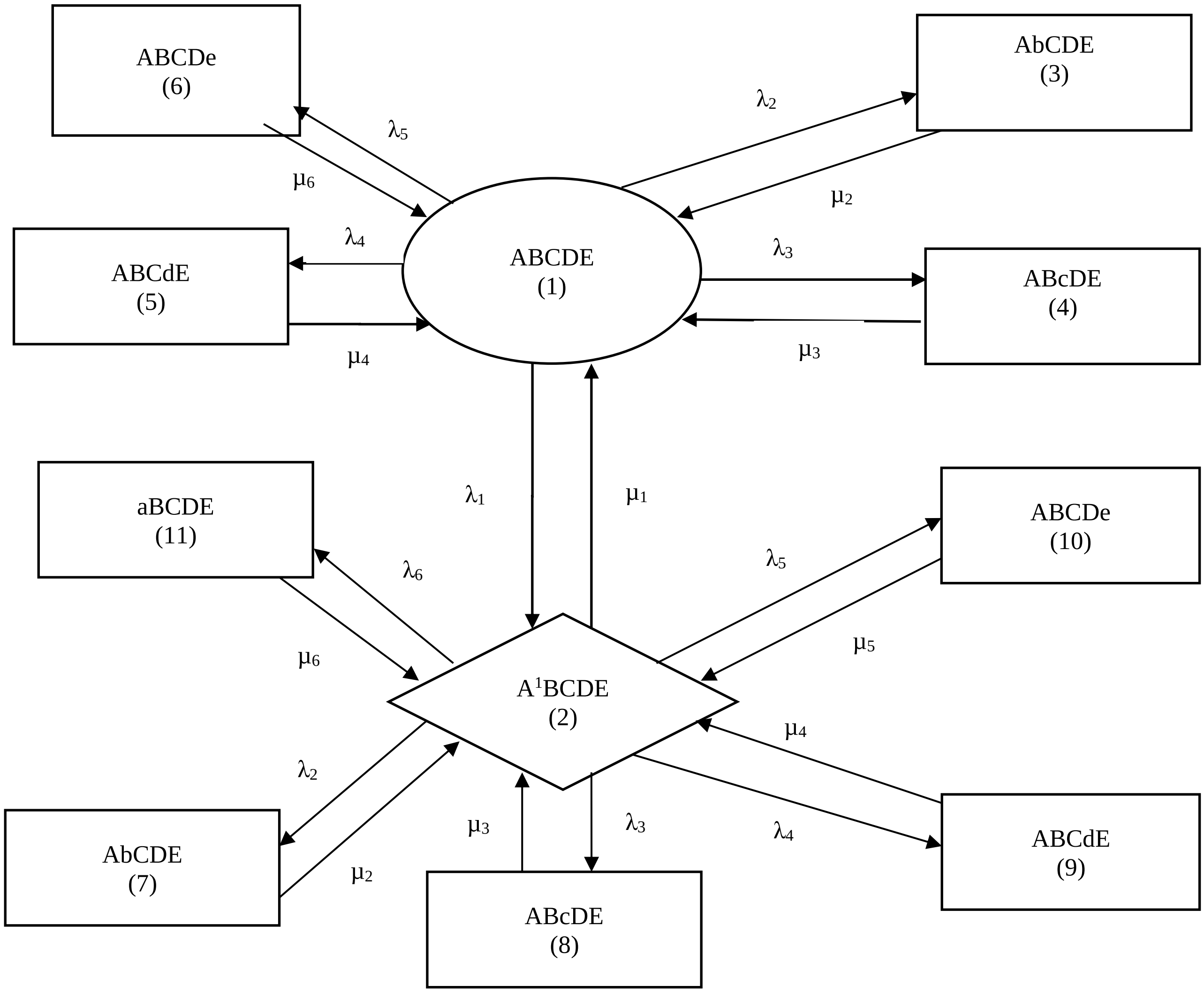

Figure 2. Transition Diagram of PET Bottle Hot Drink Filling System

3. Mathematical Modeling

Mathematical modeling of the industrial system is performed with Markov method. The various equations related with the transition diagram are as equation from (1) to (11):

$$P_1'(t) + K_1P_1(t) = \mu_1P_2(t) + \mu_2P_3(t) + \mu_3P_4(t) + \mu_4P_5(t) + \mu_5P_6(t) \quad (1)$$

$$P_2'(t) + K_2P_2(t) = \mu_2P_7(t) + \mu_3P_8(t) + \mu_4P_9(t) + \mu_6P_{11}(t) + \mu_5P_{10}(t) + \lambda_1P_1(t) \quad (2)$$

Where $K_1 = (\lambda_1 + \lambda_2 + \mu_3 + \lambda_4 + \lambda_5)$ and $K_2 = (\lambda_2 + \mu_1 + \lambda_3 + \lambda_5 + \lambda_4 + \lambda_6)$

$$P_3'(t) + \mu_2P_3(t) = \lambda_2P_1(t) \quad (3)$$

$$P_4'(t) + \mu_3P_4(t) = \lambda_3P_1(t) \quad (4)$$

$$P_5'(t) + \mu_4P_5(t) = \lambda_4P_1(t) \quad (5)$$

$$P_6'(t) + \mu_5P_6(t) = \lambda_5P_1(t) \quad (6)$$

$$P_7'(t) + \mu_2P_7(t) = \lambda_2P_2(t) \quad (7)$$

$$P_8'(t) + \mu_3P_8(t) = \lambda_3P_2(t) \quad (8)$$

$$P_9'(t) + \mu_4P_9(t) = \lambda_4P_2(t) \quad (9)$$

$$P_{10}'(t) + \mu_5P_{10}(t) = \lambda_2P_2(t) \quad (10)$$

$$P_{11}'(t) + \mu_6P_{11}(t) = \lambda_6P_2(t) \quad (11)$$

With initial conditions:

$$P_i(t) = \begin{cases} 1, if\ i = 1 \\ 0, if\ i \neq 1 \end{cases} \quad (12)$$

The equations from (1) to (11) with initial conditions have been resolved by changeable step size control Runge–Kutta method to find TDSA. Following conditions are being taken for computation:

(i) The failure and repair rates i.e. λ_1 and μ_1 of Blow Moulding machine and that of its parallel unit are λ_6 and μ_6.
(ii) Time for one year from 0 to 360 days for various values of parameters of different components of the system considered

The TDSA i.e. A(t) of the system is the addition of system working under full capacity and system working in reduced capacity i.e.

$$A(t)=P_1(t)+P_2(t) \quad (13)$$

Steady State System Availability

The industrial systems are designed to work satisfactorily for long duration of time i.e. for fifty years or more, time taken here as infinite for estimating the system availability in the long run. After doing so, we acquire: $d/dt\rightarrow 0$ as $t\rightarrow\infty$, therefore, the equations (1) to (11) are get reduced to following sets of equations.

$$K_1P_1 = \mu_1P_2 + \mu_2P_3 + \mu_3P_4 + \mu_4P_5 + \mu_5P_6 \quad (14)$$
$$K_2P_2 = \mu_2P_7 + \mu_3P_8 + \mu_4P_9 + \mu_6P_{11} + \mu_5P_{10} + \lambda_1P_1 \quad (15)$$
$$\mu_1P_2 = \lambda_1P_1 \quad (16)$$
$$\mu_2P_3 = \lambda_2P_1 \quad (17)$$
$$\mu_3P_4 = \lambda_3P_1 \quad (18)$$
$$\mu_4P_5 = \lambda_4P_1 \quad (19)$$
$$\mu_5P_6 = \lambda_5P_1 \quad (20)$$
$$\mu_2P_7 = \lambda_2P_2 \quad (21)$$
$$\mu_3P_8 = \lambda_3P_2 \quad (22)$$
$$\mu_4P_9 = \lambda_4P_2 \quad (23)$$
$$\mu_5P_{10} = \lambda_2P_2 \quad (24)$$
$$\mu_6P_{11} = \lambda_6P_2 \quad (25)$$

Now, equations (14) to (25) are solved recursively to get the value of P1 and P2 under normalizing condition

$$\sum_{i=1}^{11} P_i = 1 \text{ i.e} \quad (26)$$

The long term Availability of the system is as follows:

$$A(\infty) = \sum_{i=1}^{2} P_i \quad (27)$$

4. Time Dependent System Availability Analysis

In this section of paper the estimation of TDSA of the PET Bottle Hot Drink Filling System has been done by applying adaptive step size control Runge-Kutta method. The governing equation (13) has been solved using the above said numerical technique taking range of time (t) from 0 to 360 days with subinterval of 12. Further the MTBF has been computed using Simpson's 3/8 rule.

The data required for various variables is taken from the industry. This data is further transformed into the parametric shape as $\lambda_{1=}$ 0.0007, λ_2=0.008, λ_3=0.00035, λ_4=0.0038, λ_5=0.00008, λ_6=0.0007, μ_2=0.11, μ_3=0.05, μ_4=0.08, μ_5=0.06, μ_6=0.05, for the components A, B, C, D, and E correspondingly. The effects of parameters of various components on overall TDSA and MTBF of the system are presented in tables 1,2,3,4 and 5.

Table 1 presents that TDSA of the system increases by 1% as repair rate (μ_1) of Blow Moulding Machine increases from 0.05 to 0.125, and MTBF increases significantly by 19 days.

Table 1. Behavior pattern against the variation in the parameter of Blow Moulding Machine

	Failure Rates of Blow Moulding Machine (λ_1)				**Repair Rates of Blow Moulding Machine (μ_1)**				Constant Parameters
Days	0.0007	0.0008	0.0009	0.001	0.05	0.08	0.1	0.125	λ_2=0.008 λ_3=0.00035 λ_4=0.0038 λ_5=0.00008 λ_6=0.0007 μ_1=0.05 μ_2=0.11 μ_3=0.05 μ_4=0.08 μ_5=0.06 μ_6=0.05
0	1	1	1	1	1	1	1	1	
30	0.8851	0.8842	0.8832	0.8823	0.8851	0.8885	0.8908	0.8936	
60	0.8711	0.8689	0.8667	0.8646	0.8711	0.8789	0.8841	0.8906	
90	0.8612	0.8577	0.8542	0.8507	0.8612	0.8731	0.8811	0.8912	
120	0.8511	0.8462	0.8414	0.8366	0.8511	0.8667	0.8773	0.8906	
150	0.8406	0.8343	0.8281	0.8219	0.8406	0.8595	0.8724	0.8887	
180	0.8297	0.8220	0.8143	0.8067	0.8297	0.8516	0.8664	0.8854	
210	0.8186	0.8093	0.8002	0.7911	0.8186	0.8429	0.8596	0.8809	
240	0.8071	0.7964	0.7857	0.7753	0.8071	0.8336	0.8519	0.8753	
270	0.7954	0.7832	0.7711	0.7591	0.7954	0.8238	0.8434	0.8687	
300	0.7835	0.7698	0.7562	0.7428	0.7835	0.8135	0.8343	0.8612	
330	0.7715	0.7562	0.7412	0.7264	0.7715	0.8028	0.8246	0.8529	
360	0.7594	0.7426	0.7261	0.7099	0.7594	0.7918	0.8144	0.8438	
MTBF	**299.45**	**296.59**	**293.77**	**290.99**	**299.45**	**306.54**	**311.41**	**317.68**	

Likewise, Table 2 shows the outcome of repair rate (μ_2) of filling machine on system, TDSA increases by 2.07% as μ_2 rises from 0.11 to 0.2, MTBF is rises slightly 3 days.

Table 2. Behavior pattern against the variation in the parameter of Filling Machine

	Failure Rates of Filling Machine (λ_2)				**Repair Rates of Filling Machine (μ_2)**				Constant Parameters
Days	0.008	0.009	0.095	0.01	0.11	0.15	0.18	0.2	λ_1=0.0007 λ_3=0.00035 λ_4=0.0038 λ_5=0.00008 λ_6=0.0007 μ_1=0.05 μ_3=0.05 μ_4=0.08 μ_5=0.06 μ_6=0.05
0	1	1	1	1	1	1	1	1	
30	0.8851	0.8782	0.8747	0.8713	0.8851	0.8971	0.9029	0.9058	
60	0.8711	0.8642	0.8608	0.8575	0.8711	0.8816	0.8864	0.8888	
90	0.8612	0.8543	0.8510	0.8476	0.8612	0.8697	0.8735	0.8754	
120	0.8511	0.8442	0.8408	0.8375	0.8511	0.8579	0.8609	0.8623	
150	0.8406	0.8337	0.8302	0.8268	0.8406	0.8461	0.8483	0.8494	
180	0.8297	0.8227	0.8192	0.8157	0.8297	0.8341	0.8357	0.8365	
210	0.8186	0.8113	0.8077	0.8042	0.8186	0.8220	0.8231	0.8236	
240	0.8071	0.7997	0.7960	0.7924	0.8071	0.8098	0.8105	0.8107	
270	0.7954	0.7878	0.7840	0.7803	0.7954	0.7976	0.7979	0.7979	

300	0.7835	0.7757	0.7719	0.7681	0.7835	0.7853	0.7853	0.7851	
330	0.7715	0.7635	0.7596	0.7557	0.7715	0.7730	0.7728	0.7724	
360	0.7594	0.7512	0.7472	0.7433	0.7594	0.7607	0.7603	0.7598	
MTBF	**299.45**	**296.91**	**295.65**	**294.42**	**299.45**	**301.29**	**302.00**	**302.32**	

Table 3 reveals that by varying the repair rate of cooling machine i.e $\mu_{3=}$ 0.05 to 0.11 the TDSA increases a bit by 0.20% and the MTBF increases slightly by 1 day.

Table 3. Behavior pattern against the variation in the parameter of Cooling Machine

	Failure Rates of Cooling Machine (λ_3)				**Repair Rates of Cooling Machine (μ_3)**				**Constant Parameters**
Days	0.00035	0.0005	0.0007	0.0009	0.05	0.07	0.09	0.11	λ_1=0.0007 λ_2=0.008 λ_4=0.0038 λ_5=0.00008 λ_6=0.0007 μ_1=0.05 μ_2=0.11 μ_3=0.05 μ_4=0.08 μ_5=0.06 μ_6=0.05
0	1	1	1	1	1	1	1	1	
30	0.8851	0.8832	0.8807	0.8781	0.8851	0.8860	0.8866	0.8871	
60	0.8711	0.8689	0.8660	0.8631	0.8711	0.8724	0.8733	0.8738	
90	0.8612	0.8589	0.8560	0.8531	0.8612	0.8626	0.8635	0.8640	
120	0.8511	0.8489	0.8460	0.8431	0.8511	0.8526	0.8534	0.8539	
150	0.8406	0.8385	0.8356	0.8328	0.8406	0.8420	0.8429	0.8434	
180	.0003	0.8277	0.8249	0.8222	0.8297	0.8312	0.8319	0.8324	
210	0.8186	0.8165	0.8139	0.8112	0.8186	0.8199	0.8207	0.8212	
240	0.8071	0.8051	0.8025	0.7999	0.8071	0.8084	0.8092	0.8096	
270	0.7954	0.7935	0.7910	0.7885	0.7954	0.7967	0.7974	0.7979	
300	0.7835	0.7817	0.7792	0.7768	0.7835	0.7848	0.7855	0.7859	
330	0.7715	0.7697	0.7673	0.7650	0.7715	0.7727	0.7734	0.7738	
360	0.7594	0.7576	0.7553	0.7531	0.7594	0.7605	0.7612	0.76165	
MTBF	**299.45**	**298.74**	**297.81**	**296.90**	**299.45**	**299.90**	**300.17**	**300.20**	

Table 4 highlights that increase of repair rate of coding machine i.e. μ_4 from 0.08 to 0.150 the TDSA increases considerably by 1.52% and MTBF increases about 5 days.

Table 4. Behavior pattern against the variation in the parameter of Coding Machine

	Failure Rates of Coding Machine (λ_4)				**Repair Rates of Coding Machine (μ_4)**				Constant Parameters
Days	0.0038	0.007	0.009	0.012	0.08	0.1	0.125	0.15	λ_1=0.0007 λ_2=0.008 λ_3=0.00035 λ_5=0.00008
0	1	1	1	1	1	1	1	1	
30	0.8851	0.8521	0.8394	0.8149	0.8851	0.8911	0.8964	0.9003	
60	0.8711	0.8373	0.8243	0.7996	0.8711	0.8783	0.8842	0.8882	
90	0.8612	0.8280	0.8153	0.7911	0.8612	0.8683	0.8742	0.8781	

120	0.8511	0.8187	0.8063	0.7826	0.8511	0.8581	0.8638	0.8676	λ_6=0.0007
150	0.8406	0.8090	0.7969	0.7737	0.8406	0.8475	0.8530	0.8567	μ_1=0.05
180	0.8297	0.7990	0.7871	0.7645	0.8297	0.8364	0.8418	0.8455	μ_2=0.11
210	0.8186	0.7886	0.7771	0.7550	0.8186	0.8251	0.8303	0.8338	μ_3=0.05
240	0.8071	0.7780	0.7668	0.7453	0.8071	0.8134	0.8185	0.8219	μ_5=0.06
270	0.7954	0.7672	0.7563	0.7354	0.7954	0.8015	0.8065	0.8098	μ_6=0.05
300	0.7835	0.7561	0.7456	0.7253	0.7835	0.7895	0.7943	0.7975	
330	0.7715	0.7450	0.7348	0.7151	0.7715	0.7772	0.7819	0.7850	
360	0.7594	0.7337	0.7238	0.7048	0.7594	0.7649	0.7694	0.7724	
MTBF	**299.45**	**288.86**	**284.79**	**276.98**	**299.45**	**301.70**	**303.54**	**304.78**	

Table 5 depicts the effect of increase of repair rate of labeling machine i.e. $\mu_{5=}$ 0.06 to 0.125 the TDSA increases marginally by 0.15% and MTBF increased by 2 days.

Table 5. Behavior pattern against the variation in the parameter of Labeling Machine

	Failure Rates of Labeling Machine (λ_5)				**Repair Rates of Labeling Machine (μ_5)**				Constant Parameters
Days	0.00008	0.000085	0.000095	0.0001	0.06	0.08	0.095	0.125	
0	1	1	1	1	1	1	1	1	
30	0.8851	0.8851	0.8849	0.8849	0.8851	0.8853	0.8855	0.8857	λ_1=0.0007
60	0.8711	0.8710	0.8709	0.8708	0.8711	0.8715	0.8717	0.8721	λ_2=0.008
90	0.8612	0.8611	0.8610	0.8609	0.8612	0.8619	0.8623	0.8628	λ_3=0.0035
120	0.8511	0.8510	0.8509	0.8508	0.8511	0.8522	0.8529	0.8537	λ_4=0.0038
150	0.8406	0.8405	0.8404	0.8404	0.8406	0.8423	0.8432	0.8444	λ_6=0.0007
180	0.8297	0.8297	0.8296	0.8295	0.8297	0.8321	0.8333	0.8350	μ_1=0.05
210	0.8186	0.8185	0.8184	0.8183	0.8186	0.8217	0.8233	0.8255	μ_2=0.11
240	0.8071	0.8070	0.8069	0.8069	0.8071	0.8110	0.8130	0.8158	μ_3=0.05
270	0.7954	0.7954	0.7952	0.7952	0.7954	0.8001	0.8026	0.8061	μ_4=0.08
300	0.7835	0.7835	0.7834	0.7833	0.7835	0.7891	0.7921	0.7962	μ_5=0.06
330	0.7715	0.7715	0.7714	0.7713	0.7715	0.7780	0.7814	0.7862	μ_6=0.05
360	0.7594	0.7593	0.7592	0.7592	0.7594	0.7667	0.7706	0.7762	
MTBF	**299.45**	**299.43**	**299.38**	**299.36**	**299.45**	**300.46**	**301.00**	**301.75**	

The table 6 demonstrate the effect of repair priorities of every component on TDSA of the system and also presented suggested maintenance repair priorities of various component of the system considered.

Table 6. Suggested Maintenance Priorities on the basis of TDSA analysis

Sr. No.	**Units**	**Repair Priorities**	**% Increase in TDSA**	**Suggested Maintenance Priorities**
1.	Blow Moulding Machine	0.05-0.125	0.85	III
2	Filling Machine	0.11-0.20	2.07	I
3	Cooling Machine	0.05-0.15	0.20	IV
4.	Coding Machine	0.08-0.15	1.52	II
5.	Labeling Machine	0.06-0.125	0.15	V

5. Conclusions

The Time Dependent System Availability (TDSA) and MTBF of the PET bottle hot drink filling unit in a beverage plant has found out. The outcomes are presented in table 1 to 5 shows that effect of subsystem's parameters on TDSA of the system concerned. The filling machine (B) highly affects the TDSA of the system, augment in its repair rate enhances performance by 2.07% and MTBF improves by 6 days. On the basis of TDSA analysis the maintenance priorities has been suggested and presented in Table 6. It shows that subsystem B is the most critical system having maximum impact on TDSA of the system, Thereafter subsystem D,A,C and E are assigned priorities respectively.

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