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Reliability Analysis of a Single Machine Subsystem of a Cable Plant with Six Maintenance Categories

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Abstract – The paper presents a reliability analysis of a single machine subsystem of a cable plant. Seven years maintenance data of a cable plant have been collected. Six types of maintenance practices noted for the subsystem: electrical repair, electronic repair, mechanical repair, thermal repair, minor preventive maintenances and major scheduled preventive maintenances. The subsystem is repaired on normal failures and minor preventive maintenances are performed at random whereas the major preventive maintenances are carried out on scheduled basis. Subsystem is analyzed using semi Markov process and regenerative point technique. Reliability indices of interest such as mean time to subsystem failure, availability of the subsystem, expected busy period of the repairman and expected number of subsystem repairs, are obtained. Simulated results are shown through necessary graphs.

Keywords - reliability, semi Markov process, regenerative point technique, failure, repair, preventive maintenance, cable plant.

NOTATIONS

MTSF	Mean time to subsystem failure
MPM	Minor preventive maintenance
MSPM	Major scheduled preventive maintenance
PM	Preventive maintenance
S_i	State i
α_1	Estimated value of rate of requirement of MPM
α_2	Estimated value of rate of requirement of MSPM
β_1	Estimated value of electrical failure rate
β_2	Estimated value of electronic failure rate
β_3	Estimated value of mechanical failure rate
β_4	Estimated value of thermal failure rate
pdf	Probability density function
$f_1(t)$	pdf of MPM times
$f_2(t)$	pdf of MSPM times
$g_1(t)$	pdf of electrical repair times
$g_2(t)$	pdf of electronic repair times
$g_3(t)$	pdf of mechanical repair times
$g_4(t)$	pdf of thermal repair times
λ_1	Estimated value rate of performing MPM
λ_2	Estimated value of rate of performing MSPM
γ_1	Estimated value of electrical repair rate
γ_2	Estimated value of electronic repair rate
γ_3	Estimated value of mechanical repair rate
γ_4	Estimated value of thermal repair rate
Q_{ij}	Cumulative distribution function from S_i to S_j
q_{ij}	pdf from S_i to S_j
©	Laplace convolution
Ⓢ	Laplace Stieltje's convolution
*/LT	Laplace transform
**/LST	Laplace Stieltje's transform

I. INTRODUCTION

Many researchers have contributed in the area of reliability modeling and analysis while dealing with real industrial problems under different operating conditions and assumptions. Rizwan et al. [1-3] wrote about real case analysis of a hot standby system and desalination plant where the reliability indices of interest are obtained and the cost benefit analysis of the systems are carried out. Padmavathi et al. [4] further analysed an evaporator of a desalination plant with online repair and emergency shutdowns. Mathew et al. [5-7] discussed the reliability of a continuous casting plant operataing under different conditions. Gupta and Gupta [8] performed stochastic analysis of a one unit system with post inspection, post repair, preventive maintenance and replacement. Rizwan et al. [9] discussed a general model for reliability analysis of a domestic waste water treatment plant. Malhotra and Taneja [10] analysed a two unit cold standby system where the operation of units is demand dependent. Recently, Rizwan et al. [11] carried out reliability and availability analysis of an anaerobic batch reactor treating fruit and vegetable waste. For general reference, a book authored by Way Kuo and Ming J. Zuo [12] may be consulted. Thus, methodology for system analysis under various failure and maintenance assumptions has been widely presented in the literature and the novelty of this work lies in its case study. Electric cables being widely used in construction industry, and therefore the analysis of cable manufacturing plants is of great importance from reliability perspective. The numerical results obtained in terms of reliability indices are helpful in understanding the significance of these failures/maintenances on cable plant availability and assess the impact of these failures on the overall profitability of the plant.

Thus, the paper is an attempt to present the case analysis of a single machine subsystem of a cable plant using the maintenence data of seven years from operations and maintenance reports of a cable plant in Sultanate of Oman. Based on the various operating states of the subsystem, a detailed subsystem analysis is carried out using semi Markov process and regenerative point technique. Outcome of the entire analysis is measured in terms of overall system effectiveness such as mean time to subsystem failure (MTSF), availability of the subsystem, expected busy period of the repairman and expected number of subsystem repairs. Simulated results are demonstrated graphically.

II. DESCRIPTION OF THE SUBSYSTEM

Maintenance data of the cable plant depicts six types of maintenances for the subsystem i.e. electrical repair, electronic repair, mechanical repair, thermal repair, minor preventive maintenance (MPM) and major scheduled preventive maintenance (MSPM). Possible transition states of the subsystem are described below:

State 0 (S_0): subsystem is operative

State 1 (S_1): subsystem is down, undergoing MPM

State 2 (S_2): subsystem is down, undergoing MSPM

State 3 (S_3): subsystem has failed, undergoing electrical repair

State 4 (S_4): subsystem has failed, undergoing electronic repair

State 5 (S_5): subsystem has failed, undergoing mechanical repair

State 6 (S_6): subsystem has failed, undergoing thermal repair

The subsystem regenerates and works as new after preventive maintenance (PM) or repair is carried out. Table 1 gives the rates of transition from S_i to S_j. 0 denotes for no transition to the mentioned state. Failure rates are taken as exponential whereas repair/PM rates are arbitrary.

S_i \ S_j	S_0	S_1	S_2	S_3	S_4	S_5	S_6
S_0	0	α_1	α_2	β_1	β_2	β_3	β_4
S_1	$f_1(t)$	0	0	0	0	0	0
S_2	$f_2(t)$	0	0	0	0	0	0
S_3	$g_1(t)$	0	0	0	0	0	0
S_4	$g_2(t)$	0	0	0	0	0	0
S_5	$g_3(t)$	0	0	0	0	0	0
S_6	$g_4(t)$	0	0	0	0	0	0

Table 1: Rates for the subsystem

Table 2 shows the values of rates of repair/failure and rates of performing/requirement of PM estimated for the subsystem from the maintenance data of the plant.

S.No.	Rate (/hour)	Value (/hour)
1	α_1, rate of requirement of MPM	0.001423033
2	α_2, rate of requirement of MSPM	0.000463760
3	β_1, electrical failure rate	0.002133241
4	β_2, electronic failure rate	0.000390684
5	β_3, mechanical failure rate	0.002454124
6	β_4, thermal failure rate	0.000892342
7	λ_1, rate of performing MPM	0.854700855
8	λ_2, rate of performing MSPM	0.043887147
9	γ_1, electrical repair rate	0.150557407
10	γ_2, electronic repair rate	0.190779014
11	γ_3, mechanical repair rate	0.136066763
12	γ_4, thermal repair rate	0.181147266

Table2: Estimated values of rates for the subsystem

III. TRANSITON PROBABILITIES AND MEAN SOJOURN TIMES

Possible transition states of the subsystem are described in section II. S_0, S_1, S_2, S_3, S_4, S_5, and S_6 are regenerative states from where the subsystem regenerates after PM or repair as necessary.

Transition probabilities from S_i to S_j are given by equations (1-12)

$$dQ_{01}(t) = \alpha_1 e^{-(\alpha_1+\alpha_2+\beta_1+\beta_2+\beta_3+\beta_4)t}dt \quad (1)$$
$$dQ_{02}(t) = \alpha_2 e^{-(\alpha_1+\alpha_2+\beta_1+\beta_2+\beta_3+\beta_4)t}dt \quad (2)$$
$$dQ_{03}(t) = \beta_1 e^{-(\alpha_1+\alpha_2+\beta_1+\beta_2+\beta_3+\beta_4)t}dt \quad (3)$$
$$dQ_{04}(t) = \beta_2 e^{-(\alpha_1+\alpha_2+\beta_1+\beta_2+\beta_3+\beta_4)t}dt \quad (4)$$
$$dQ_{05}(t) = \beta_3 e^{-(\alpha_1+\alpha_2+\beta_1+\beta_2+\beta_3+\beta_4)t}dt \quad (5)$$
$$dQ_{06}(t) = \beta_4 e^{-(\alpha_1+\alpha_2+\beta_1+\beta_2+\beta_3+\beta_4)t}dt \quad (6)$$
$$dQ_{10}(t) = f_1(t)dt \quad (7)$$
$$dQ_{20}(t) = f_2(t)dt \quad (8)$$
$$dQ_{30}(t) = g_1(t)dt \quad (9)$$
$$dQ_{40}(t) = g_2(t)dt \quad (10)$$
$$dQ_{50}(t) = g_3(t)dt \quad (11)$$
$$dQ_{60}(t) = g_4(t)dt \quad (12)$$

Using the definition [1] of nonzero elements p_{ij}, we get equations (13-24)

$$p_{01} = \frac{\alpha_1}{\alpha_1+\alpha_2+\beta_1+\beta_2+\beta_3+\beta_4} \quad (13)$$
$$p_{02} = \frac{\alpha_2}{\alpha_1+\alpha_2+\beta_1+\beta_2+\beta_3+\beta_4} \quad (14)$$
$$p_{03} = \frac{\beta_1}{\alpha_1+\alpha_2+\beta_1+\beta_2+\beta_3+\beta_4} \quad (15)$$
$$p_{04} = \frac{\beta_2}{\alpha_1+\alpha_2+\beta_1+\beta_2+\beta_3+\beta_4} \quad (16)$$
$$p_{05} = \frac{\beta_3}{\alpha_1+\alpha_2+\beta_1+\beta_2+\beta_3+\beta_4} \quad (17)$$
$$p_{06} = \frac{\beta_4}{\alpha_1+\alpha_2+\beta_1+\beta_2+\beta_3+\beta_4} \quad (18)$$
$$p_{10} = f_1^*(0) \quad (19)$$
$$p_{20} = f_2^*(0) \quad (20)$$
$$p_{30} = g_1^*(0) \quad (21)$$
$$p_{40} = g_2^*(0) \quad (22)$$
$$p_{50} = g_3^*(0) \quad (23)$$
$$p_{60} = g_4^*(0) \quad (24)$$

Equations (25-26) can be easily verified

$$p_{01} + p_{02} + p_{03} + p_{04} + p_{05} + p_{06} = 1 \quad (25)$$
$$p_{10} = p_{20} = p_{30} = p_{40} = p_{50} = p_{60} = 1 \quad (26)$$

Using the definition [1] of mean sojourn time μ_i, we get equations (27-33)

$$\mu_0 = \frac{1}{\alpha_1+\alpha_2+\beta_1+\beta_2+\beta_3+\beta_4} \quad (27)$$
$$\mu_1 = \int_0^\infty tf_1(t)dt \quad (28)$$
$$\mu_2 = \int_0^\infty tf_2(t)dt \quad (29)$$
$$\mu_3 = \int_0^\infty tg_1(t)dt \quad (30)$$
$$\mu_4 = \int_0^\infty tg_2(t)dt \quad (31)$$
$$\mu_5 = \int_0^\infty tg_3(t)dt \quad (32)$$
$$\mu_6 = \int_0^\infty tg_4(t)dt \quad (33)$$

IV. RELIABILITY ANALYSIS

A. MTSF

Consider the failed states 3, 4, 5 and 6 of the subsystem as absorbing states. Using simple probabilistic arguments and the definition [1] of $\phi_i(t)$, we get equations (34-36)

$$\phi_0(t) = Q_{01}(t)Ⓢ\phi_1(t)+Q_{02}(t)Ⓢ\phi_2(t)+ Q_{03}(t)+Q_{04}(t)+Q_{05}(t)+Q_{06}(t) \quad (34)$$
$$\phi_1(t) = Q_{10}(t)Ⓢ\phi_0(t) \quad (35)$$
$$\phi_2(t) = Q_{20}(t)Ⓢ\phi_0(t) \quad (36)$$

Taking Laplace Stieltjes transform (LST) of equations (34-36) and solving for $\phi_0^{**}(s)$, we obtain equation (37)

$$\phi_0^{**}(s) = \frac{N(s)}{D(s)} \quad (37)$$

MTSF when the subsystem started at the beginning of state 0 is given by equation (38)

$$\mathrm{MTSF} = \lim_{s\to 0} \frac{1-\phi_0^{**}(s)}{s} = \frac{N}{D} \quad (38)$$

where

$N = \mu_0 + p_{01}\mu_1 + p_{02}\mu_2$

$D = p_{03} + p_{04} + p_{05} + p_{06}$

B. Availability of the subsystem

Using simple probabilistic arguments and the definition [1] of $A_i(t)$, we get equations (39-45)

$$A_0(t) = M_0(t)+q_{01}(t)\copyright A_1(t)+q_{02}(t)\copyright A_2(t)+q_{03}(t)\copyright A_3(t)+ q_{04}(t)\copyright A_4(t)+q_{05}(t)\copyright A_5(t)+q_{06}(t)\copyright A_6(t) \quad (39)$$

$$A_1(t) = q_{10}(t)\copyright A_0(t) \quad (40)$$

$$A_2(t) = q_{20}(t)\copyright A_0(t) \quad (41)$$

$$A_3(t) = q_{30}(t)\copyright A_0(t) \quad (42)$$

$$A_4(t) = q_{40}(t)\copyright A_0(t) \quad (43)$$

$$A_5(t) = q_{50}(t)\copyright A_0(t) \quad (44)$$

$$A_6(t) = q_{60}(t)\copyright A_0(t) \quad (45)$$

here, $M_0(t) = e^{-(\alpha_1+\alpha_2+\beta_1+\beta_2+\beta_3+\beta_4)t}$

Taking Laplace transform (LT) of equations (39-45) and solving for $A_0^{*}(s)$, we get equation (46)

$$A_0^{*}(s) = \frac{N_1(s)}{D_1(s)} \quad (46)$$

In steady state, availability of the subsystem is given by equation (47)

$$A_0 = \lim_{s\to 0} s\, A_0^{*}(s) = \frac{N_1}{D_1} \quad (47)$$

where

$N_1 = \mu_0$

$D_1 = \mu_0 + p_{01}\mu_1 + p_{02}\mu_2 + p_{03}\mu_3 + p_{04}\mu_4 + p_{05}\mu_5 + p_{06}\mu_6$

C. Busy period of the repairman

C.I. Expected busy period of the repairman (electrical repair)

Using simple probabilistic arguments and the definition [1] of $B_i(t)$, we get equations (48-54)

$$B1_0(t) = q_{01}(t)\copyright B1_1(t)+q_{02}(t)\copyright B1_2(t)+q_{03}(t)\copyright B1_3(t)+ q_{04}(t)\copyright B1_4(t)+q_{05}(t)\copyright B1_5(t)+q_{06}(t)\copyright B1_6(t) \quad (48)$$

$$B1_1(t) = q_{10}(t)\copyright B1_0(t) \quad (49)$$

$$B1_2(t) = q_{20}(t)\copyright B1_0(t) \quad (50)$$

$$B1_3(t) = W_3(t) + q_{30}(t)\copyright B1_0(t) \quad (51)$$

$$B1_4(t) = q_{40}(t)\copyright B1_0(t) \quad (52)$$

$$B1_5(t) = q_{50}(t)\copyright B1_0(t) \quad (53)$$

$$B1_6(t) = q_{60}(t)\copyright B1_0(t) \quad (54)$$

here, $W_3(t) = \overline{G_1(t)}$

Taking LT of equations (48-54) and solving for $B1_0^{*}(s)$, we obtain equation (55)

$$B1_0^{*}(s) = \frac{N_2(s)}{D_1(s)} \quad (55)$$

In steady state, expected busy period of the repairman (electrical repair) is given by equation (56)

$$B1_0 = \lim_{s\to 0} s\, B1_0^{*}(s) = \frac{N_2}{D_1} \quad (56)$$

where

$N_2 = p_{03}\mu_3$

D_1 is already specified

Proceeding in the same way as in section C.I, the following results are achieved:

C.II. In steady state, expected busy period of the repairman (electronic repair) is given by equation (57)

$$B2_0 = \frac{N_3}{D_1} \quad (57)$$

where

$N_3 = p_{04}\mu_4$

D_1 is already specified

C.III. In steady state, expected busy period of the repairman (mechanical repair) is given by equation (58)

$$B3_0 = \frac{N_4}{D_1} \quad (58)$$

where

$N_4 = p_{05}\mu_5$

D_1 is already specified

C.IV. In steady state, expected busy period of the repairman (thermal repair) is given by equation (59)

$$B4_0 = \frac{N_5}{D_1} \quad (59)$$

where

$N_5 = p_{06}\mu_6$

D_1 is already specified

D. Number of subsystem repairs

D.I. Expected number of electrical repairs

Using simple probabilistic arguments and the definition [1] of $R_i(t)$, we get equations (59-65)

$$R1_0(t) = Q_{01}(t)\circledS R1_1(t)+Q_{02}(t)\circledS R1_2(t)+Q_{03}(t)\circledS R1_3(t)+ Q_{04}(t)\circledS R1_4(t)+Q_{05}(t)\circledS R1_5(t)+Q_{06}(t)\circledS R1_6(t) \quad (59)$$

$$R1_1(t) = Q_{10}(t)\circledS R1_0(t) \quad (60)$$

$$R1_2(t) = Q_{20}(t)\circledS R1_0(t) \quad (61)$$

$$R1_3(t) = Q_{30}(t)\circledS\{1 + R1_0(t)\} \quad (62)$$

$$R1_4(t) = Q_{40}(t)\circledS R1_0(t) \quad (63)$$

$$R1_5(t) = Q_{50}(t)\circledS R1_0(t) \quad (64)$$

$$R1_6(t) = Q_{60}(t)\circledS R1_0(t) \quad (65)$$

Taking LST of equations (59-65) and solving for $R1_0^{**}(s)$, we get equation (66)

$$R1_0^{**}(s) = \frac{N_6(s)}{D_1(s)} \quad (66)$$

In steady state, expected number of electrical repairs per unit time is given by equation (67)

$$R1_0 = \lim_{s\to 0} s\, R1_0^{**}(s) = \frac{N_6}{D_1} \quad (67)$$

where

$N_6 = p_{03}$

D_1 is already specified

Proceeding in the same way as in section D.I, the following results are achieved:

D.II. In steady state, expected number of electronic repairs per unit time is given by equation (68)

$$R2_0 = \frac{N_7}{D_1} \quad (68)$$

where

$N_7 = p_{04}$

D_1 is already specified

D.III. In steady state, expected number of mechanical repairs per unit time is given by equation (69)

$$R3_0 = \frac{N_8}{D_1} \quad (69)$$

where

$N_8 = p_{05}$

D_1 is already specified

D.IV. In steady state, expected number of thermal repairs per unit time is given by equation (70)

$$R4_0 = \frac{N_9}{D_1} \quad (70)$$

where
$N_9 = p_{06}$
D_1 is already specified

V. PARTICULAR CASE

Assume that the failure times and other times as well follow exponential distribution i.e.

$$f_1(t) = \lambda_1 e^{-\lambda_1 t} \quad (71)$$
$$f_2(t) = \lambda_2 e^{-\lambda_2 t} \quad (72)$$
$$g_1(t) = \gamma_1 e^{-\gamma_1 t} \quad (73)$$
$$g_2(t) = \gamma_2 e^{-\gamma_2 t} \quad (74)$$
$$g_3(t) = \gamma_3 e^{-\gamma_3 t} \quad (75)$$
$$g_4(t) = \gamma_4 e^{-\gamma_4 t} \quad (76)$$

Using the estimated values given in table 2 and equations 1-76, following reliability indices are obtained:
MTSF= 172.43006 hours
Availability of the subsystem = 0.95110
Expected busy period of the repairman (electrical repair) = 0.01348
Expected busy period of the repairman (electronic repair) = 0.00195
Expected busy period of the repairman (mechanical repair) = 0.01716
Expected busy period of the repairman (thermal repair) = 0.00469
Expected number of electrical repairs = 0.00203/hour
Expected number of electronic repairs = 0.00037/hour
Expected number of mechanical repairs = 0.00233/hour
Expected number of thermal repairs = 0.00085/hour

VI. GRAPHICAL INTERPRETATION

Figures 1, 2, 3 and 4 show the trend of MTSF, availability of the subsystem, expected busy period of the repairman and expected number of subsystem repairs respectively when plotted against failure rate.

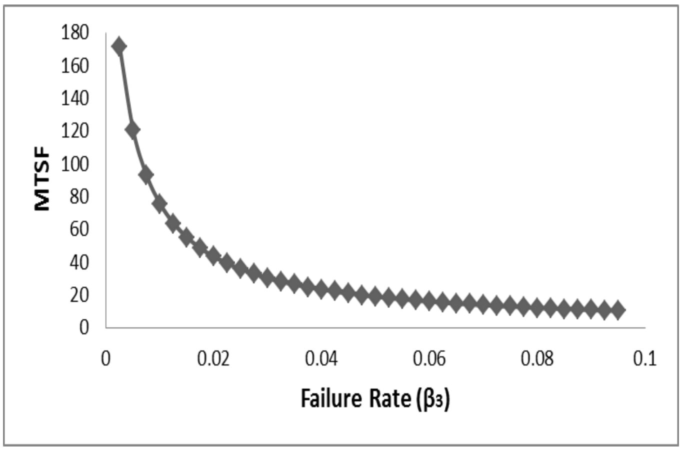

Figure 1

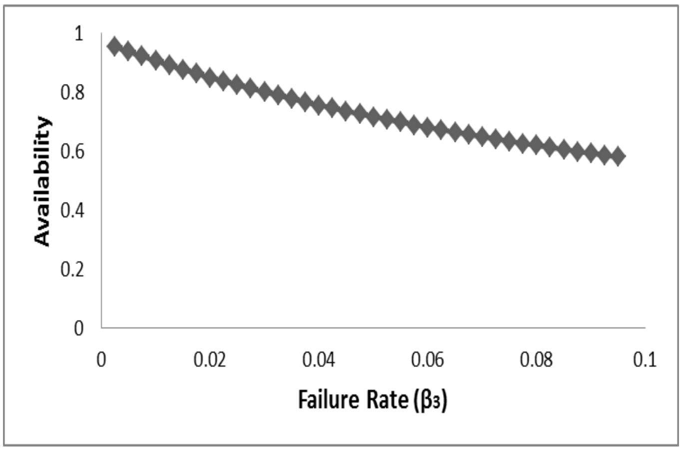

Figure 2

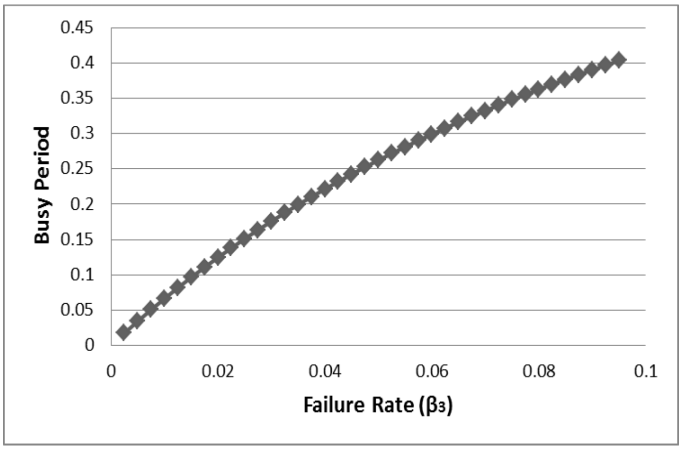

Figure 3

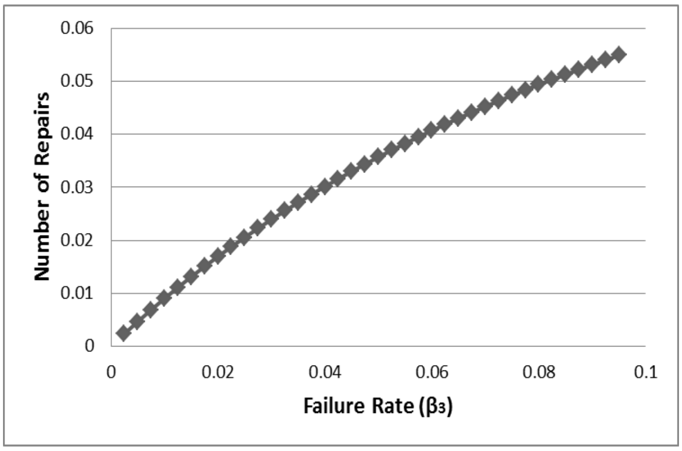

Figure 4

VII. CONCLUSION

Reliability indices for a single machine subsystem of a cable plant with six maintenance categories are obtained, to measure the sub system effectiveness in terms of mean time to subsystem failure (MTSF), availability of the subsystem, expected busy period of the repairman and expected number of subsystem repairs. Necessary simulated results are shown graphically. There is potential scope of extending the work further for double machine subsystems analysis with various online/offline maintenance strategies.

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