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Risk and reliability analysis of the selected Boeing types

Keywords

reliability analysis, risk analysis, Boeing 727, 737, 747

Abstract

This article presents the analysis of risk and reliability of the Boeings 727, 737, 747 fleet. This analysis includes the study of reliability and risk of the number of aircrafts in operation for those Boeings, considering the long list of accidents that the aircraft has suffered around all the series and the unfortunate fatalities which are the result of each catastrophe. Beside this, it is possible to see the analysis of accidents caused by each phase of flight, undesirable event and weather. Nevertheless, it is worth noting that the number of flight hours and the number of flights of the Boeings fleet, among other data, was obtained from official sources pages.

1. Introduction

Aviation is one of the safest forms of transportation, and statistics indicate that it has become even safer in the recent years. Air accidents are relatively rare, but when they do happen they could be devastating. The major objective of an aircraft accident investigation is to determine the causes of an accident and to help to establish consistent measures in order to avoid similar occurrences under related circumstances. We cannot avoid all accidents, but we ought to try. Learning from accidents and incidents in organizations and companies is a more complex process. But the only way to achieve it is to investigate thoroughly aircraft accidents occurrence.

Despite of all technology, studies and analysis, and all information obtained by more than a century, there is a simple question with a complicated general answer: ***Why do planes crash?***

In fact, much of the literature on aviation says that the only answer possible to get about this big question is the percentage given between 70% and 80% related to existing human error [11]. After all, it is well established that aviation accidents cannot be attributed to a single cause, or in most cases, even a single individual. By contrast, aviation accidents are the result of a series of causes or chains and only one last part are caused by the unsafe acts of the flight crew [10].

Moreover, there is the great challenge for both, researchers and aviation accidents analysts which are related in how to identify and mitigate the sequence of events that cause aviation accidents and especially, that 70-80% associated with human error. However, what is needed is a framework in which it is possible to develop a program surrounded by the analysis of risk and reliability of such data.

2. Probability of an Accident for every Phase of Flight for different aircrafts

For this article, nine phases of flight were chosen because they are considered by the studies of reliability, risk and human factors in aviation, as the most important phases for the analysis and study of accidental causes, whose resultant end is to avoid them. Such phases are presented as follow by taking into account their definition given by ICAO [6] and the Commercial Aviation Safety Team (CAST) in the manual of common taxonomies for aviation. Flight was divided to phases: Standing or Parking (STD), Pushback or Towing (PBT), Taxi (TXI), Takeoff (TOF), Climb (CLB), Cruise (CRZ), Descent (DCT), Approach (APR), Landing (LDG).

The probabilities of an accident $P(A_{cc})$ due to influence of phase of flight for one flight can be calculated with the following formula:

$$P\left(A_{cc}\right)=\frac{n_A}{N} \tag{1}$$

where n_A is the total number of accidents, and N is the total number of flights.

Table 1. Number and probability accidents due to influence of phase of flight for Boeing 727, 737 and 747 [4], [7], [12].

	Number of accidents			Probability of an accident		
	727	**737**	**747**	**727**	**737**	**747**
Standing or Parking (STD)	13	34	9	1.68E-07	1.93E-07	4.28E-07
Pushback or Towing (PBT)	2	18	2	2.58E-08	1.02E-07	9.50E-08
Taxi (TXI)	7	35	5	9.03E-08	1.99E-07	2.38E-07
Takeoff (TOF)	16	81	18	2.06E-07	4.60E-07	8.55E-07
Climb (CLB)	9	29	31	1.16E-07	1.65E-07	1.47E-06
Cruise (CRZ)	10	65	8	1.29E-07	3.69E-07	3.80E-07
Descent (DCT)	7	46	6	9.03E-08	2.61E-07	2.85E-07
Approach (APR)	30	75	6	3.87E-07	4.26E-07	2.85E-07
Landing (LDG)	37	98	27	4.77E-07	5.56E-07	1.28E-06

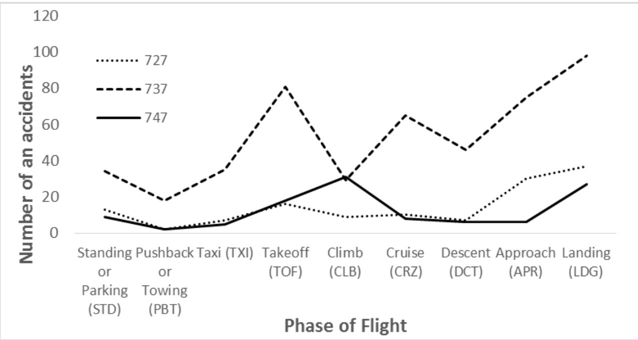

Figure 1. Number of accidents due to phase of flight

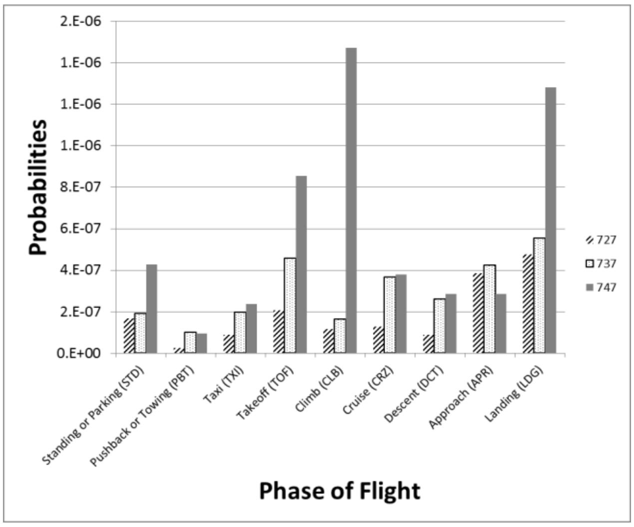

Figure 2. Probability of an accident due to phase of flight

As it was showed at *Figure 1* the highest number of accidents in analyzed Boeing fleet is different due to phases of flight. The highest possibility of accident is in the landing phase (LDG). Probability of accidents, regardless of phase of flight, is still lower than target accident rate $1 \cdot 10^{-6}$ according to [5].

3. Probability of an Accident for every Undesirable Event

The probability of an undesirable event $P(U_E)$ for one flight were calculated as follow:

$$P\left(U_E\right)=\frac{n_{UE}}{n_A}\cdot P(A_{cc})=\frac{n_{UE}}{N} \tag{2}$$

where n_{UE} is the number of undesirable events.
The number of an undesirable events [3] were obtained from [4], [7], [12] and presented in *Table 2*. The probabilities of accidents as consequences of undesirable events were obtained from (4) and presented in *Figure 3* for Boeing fleets. Total numbers of accidents was: 131 for Boeing 727, 481 for Boeing 737 and 112 accidents for Boeing 747. Total number of flights was 77.35 10^6 for Boeing 727, $176.5 \cdot 10^6$ for Boeing 737 and $21{,}01 \cdot 10^6$ for Boeing 747 [1]. It can be seen that the total number of accidents for the Boeing 747 is similar to Boeing 727 during analysed period of time, while for Boeing 737 is four times greater. It is interesting that the total numer of flights for Boeing 747 is significantly smaller than the numer of flights for Boeing 727.

Table 2. Number and probability of undesirable events for Boeing 727, 737 and 747 [4], [7], [12]

	Number of undesirable events			Probability of an undesirable event		
	727	**737**	**747**	**727**	**737**	**747**
Bad Weather	33	105	10	4.26E-07	5.96E-07	4.75E-07
Terrorist Attack	9	5	19	1.16E-07	2.84E-08	9.03E-07
Pilot Error	37	115	10	4.77E-07	6.53E-07	4.75E-07
Human Error	22	73	13	2.84E-07	4.14E-07	6.18E-07
Engine Failure	2	32	7	2.58E-08	1.82E-07	3.33E-07
Fuel System Failure	1	6		1.29E-08	3.41E-08	0
Landing Gear Failure	6	34	4	7.74E-08	1.93E-07	1.90E-07
Fire on Board	2	8	14	2.58E-08	4.54E-08	6.65E-07
Birdstrike		11	1	0	6.24E-08	4.75E-08
Structural Failures	1	9	10	1.29E-08	5.11E-08	4.75E-07
Pressurization System Failure		7		0	3.97E-08	0
Technical/Mechanical Failures	10	62	22	1.29E-07	3.52E-07	1.05E-06
Unknown Reasons	4	54		5.16E-08	3.06E-07	0
Other Failures	4	17	2	5.16E-08	9.65E-08	9.50E-08

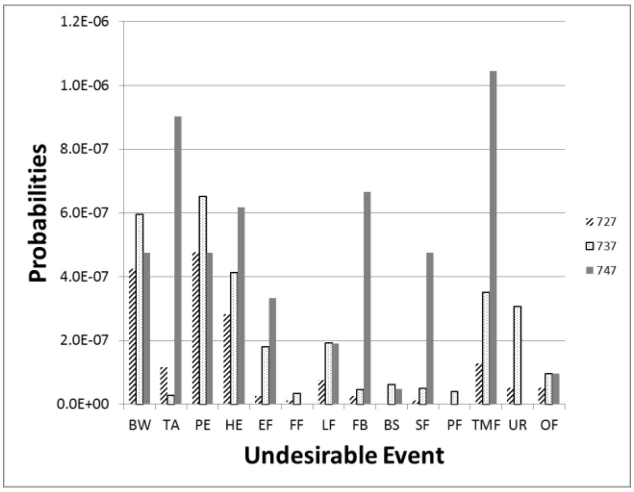

Figure 3. Probability of an undesirable event

4. Probability of an Accident due to Influence of Weather Conditions

Weather conditions are also important factors for accidents. According to statics weather conditions are responsible for 25% of Boeing 727 aircraft accidents. This percentage may increase by adding the more sub-factors relating to weather conditions for example pilot error relating bad weather, human error relating bad weather, technical error relating bad weather etc. It can be said that influence of weather conditions has largely affected the operation of global aviation [8].

The probabilities of an accident due to influence of weather conditions for one flight $P(W_c)$ can be calculated with the following formula:

$$P\left(W_c\right) = \frac{n_{WC}}{n_A} \cdot P(A_{cc}) = \frac{n_{WC}}{N} \qquad (3)$$

where n_{WC} is the number of weather condition events.

Table 3. Number and probability of an accident due to influence of weather conditions for Boeing 727, 737 and 747 [4], [7], [12]

	Number of accidents			Probability of an accident due to influence of weather conditions		
	727	737	747	727	737	747
Ice	3	4	1	3.87E-08	2.27E-08	4.75E-08
Thunderstorm	5	20	1	6.45E-08	1.14E-07	4.75E-08
of Low Visibility	3	5	1	3.87E-08	2.84E-08	4.75E-08
Wind Shear	5	5	2	6.45E-08	2.84E-08	9.50E-08
Fog	4	7	1	5.16E-08	3.97E-08	4.75E-08
Heavy Rain	7	17	4	9.03E-08	9.65E-08	1.90E-07
Ceiling		6		0	3.41E-08	0
Heavy Snow	3	6		3.87E-08	3.41E-08	0
Strong Wind	1	59		1.29E-08	3.35E-07	0
Hurricane Wilma	2			2.58E-08	0	0
Unknow		3		0	1.70E-08	0

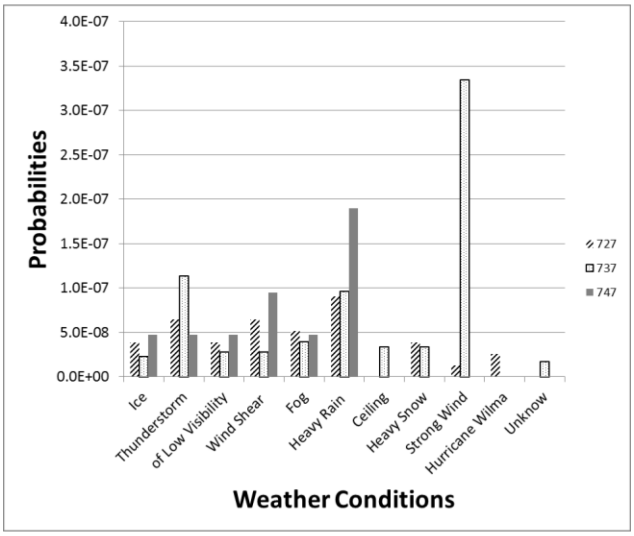

Figure 4. Probability of an accident due to influence of weather conditions

5. Risk Analysis

This risk analysis is made as a part of 'Accident Survivability'. It determines the total number of aircraft occupants died, injured or survived during all of the accidents or incidents. The results of the total risk for different categories of loss per undesirable event are also calculated and compared.

The following risk analysis has been performed by taking into account the definition of loss categories found in MIL-STD-882D Appendix A [9], and presented in *Table 4* below. Accordingly, the category c1 represents no fatalities, aircraft's damage substantial or less severe. The category c2 represents no fatalities, aircraft destroyed or damaged beyond repair. The Category c3 represents between 1÷50% of occupants' fatalities. The category c4 represents between 51÷99% of occupants' fatalities. The category c5 represents the fatalities of all (100%) occupants.

Table 4. Categories of loss

Category	Definition
c1	All Occupants with Minor Injuries or Uninjured
c2	Occupants with Major Injuries
c3	Fatalities less than 50%
c4	Fatalities more than 50% but less than 100%
c5	Fatalities of all occupants or people involved in the accident

Figure 5 presents the total number of accidents classified in each category of loss. As seen clearly that maximum number of accidents or incidents occurred in category c1.

The formula of occurrence of every category of loss for every undesirable event p_j is presented as follow [13]:

$$p_j = \frac{N_{A-UE}|c_i}{N_{A-UE}} \tag{4}$$

where $N_{A\text{-}UE}|c_i$ is the total number accidents per category of loss in the undesirable events, $N_{A\text{-}UE}$ is the total number accidents of the undesirable events.

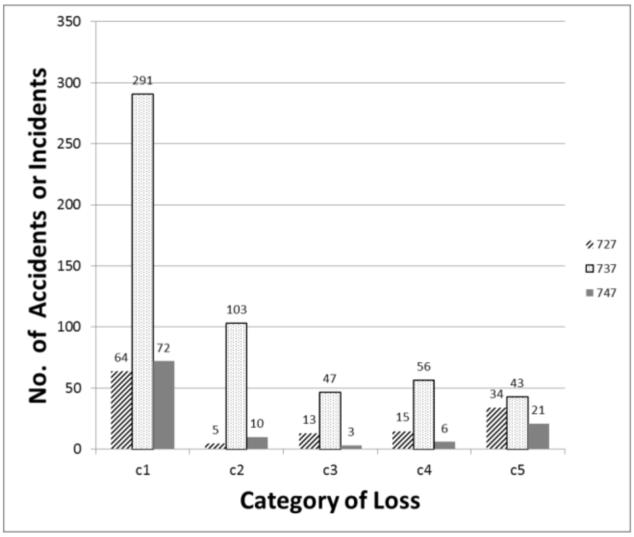

Figure 5. Total number of accidents per category of loss

The measure of hazard ($Z(cj)$) per undesirable event was calculated according to the following formulas [13]:

$$\begin{aligned} Z(c1) &= p_1 + p_2 + p_3 + p_4 + p_5 \\ Z(c2) &= p_2 + p_3 + p_4 + p_5 \\ Z(c3) &= p_3 + p_4 + p_5 \\ Z(c4) &= p_4 + p_5 \\ Z(c5) &= p_5 \end{aligned} \tag{5}$$

Resulting risk on every flight and each category of loss R, combined with the results of each undesirable event was calculated as follows [13]:

$$R\left(\frac{1}{Flight} \right)_{UE} = P(U_E) \cdot Z(cj) \tag{6}$$

Therefore, *Table 5* shows the results of 'Measure of hazards' ($Z(cj)$) and results of 'Measure of Risk' for the category of loss per every undesirable event regarding one flight of the Boeing fleet. The *Figure 6* shows the results for the total risk based on calculations visible in *Table 5*.

Table 5. Total Risk Measure

Bad Weather					
	c1	**c2**	**c3**	**c4**	**c5**
727 Z(Cj)	1	0.61	0.55	0.55	0.21
737 Z(Cj)	1	0.73	0.27	0.14	0.05
747 Z(Cj)	1	0.50	0.30	0.30	0.10
727 R[1/flight]	4.26E-07	2.58E-07	2.32E-07	2.32E-07	9.03E-08
737 R[1/flight]	5.96E-07	4.35E-07	1.61E-07	8.34E-08	2.98E-08
747 R[1/flight]	4.75E-07	2.38E-07	1.43E-07	1.43E-07	4.75E-08
Terrorist Attack					
727 Z(Cj)	1	0.67	0.67	0.44	0.33
737 Z(Cj)	1	0.80	0.80	0.80	0.40
747 Z(Cj)	1	0.26	0.11	0.11	0.05
727 R[1/flight]	1.16E-07	7.74E-08	7.74E-08	5.16E-08	3.87E-08
737 R[1/flight]	2.84E-08	2.27E-08	2.27E-08	2.27E-08	1.14E-08
737 R[1/flight]	9.03E-07	2.38E-07	9.50E-08	9.50E-08	4.75E-08
Pilot Error					
727 Z(Cj)	1	0.70	0.62	0.43	0.38
737 Z(Cj)	1	0.36	0.23	0.15	0.04
747 Z(Cj)	1	0.45	0.18	0.18	0.18
727 R[1/flight]	4.77E-07	3.35E-07	2.97E-07	2.06E-07	1.81E-07
737 R[1/flight]	6.53E-07	2.35E-07	1.50E-07	9.79E-08	2.61E-08
737 R[1/flight]	4.75E-07	2.16E-07	8.64E-08	8.64E-08	8.64E-08
Human Error					
727 Z(Cj)	1	0.36	0.36	0.27	0.23
737 Z(Cj)	1	0.26	0.12	0.05	0.01
747 Z(Cj)	1	0.62	0.62	0.62	0.38
727 R[1/flight]	2.84E-07	1.03E-07	1.03E-07	7.74E-08	6.45E-08
737 R[1/flight]	4.14E-07	1.08E-07	4.97E-08	2.07E-08	4.14E-09
737 R[1/flight]	6.18E-07	3.80E-07	3.80E-07	3.80E-07	2.38E-07
Fuel System Failure					
727 Z(Cj)	1	1.00	1.00	1.00	1.00
737 Z(Cj)	1	0.50	0.34	0.34	0.17
747 Z(Cj)					
727 R[1/flight]	1.29E-08	1.29E-08	1.29E-08	1.29E-08	1.29E-08
737 R[1/flight]	3.41E-08	1.70E-08	1.16E-08	1.16E-08	5.79E-09
737 R[1/flight]					
Landing Gear Failure					
727 Z(Cj)	1				
737 Z(Cj)	1	0.29	0.15	0.09	
747 Z(Cj)	1				
727 R[1/flight]	7.74E-08				
737 R[1/flight]	1.93E-07	5.60E-08	2.89E-08	1.74E-08	
737 R[1/flight]	1.90E-07				
Fire On Board					
727 Z(Cj)	1	0.50	0.50	0.50	0.50
737 Z(Cj)	1	0.63	0.63	0.25	
747 Z(Cj)	1	0.64	0.50	0.50	0.50
727 R[1/flight]	2.58E-08	1.29E-08	1.29E-08	1.29E-08	1.29E-08
737 R[1/flight]	4.54E-08	2.86E-08	2.86E-08	1.14E-08	
737 R[1/flight]	6.65E-07	4.28E-07	3.33E-07	3.33E-07	3.33E-07
Birdstrike					
727 Z(Cj)					
737 Z(Cj)	1	0.45	0.27	0.18	
747 Z(Cj)	1	1	1	1	1
727 R[1/flight]					
737 R[1/flight]	6.24E-08	2.81E-08	1.69E-08	1.12E-08	
737 R[1/flight]	4.75E-08	4.75E-08	4.75E-08	4.75E-08	4.75E-08
Structural Failure					
727 Z(Cj)	1				
737 Z(Cj)	1	0.22	0.11	0.11	
747 Z(Cj)	1	0.63	0.50	0.38	0.25
727 R[1/flight]	1.29E-08				
737 R[1/flight]	5.11E-08	1.12E-08	5.62E-09	5.62E-09	
737 R[1/flight]	4.75E-07	2.97E-07	2.38E-07	1.78E-07	1.19E-07
Pressurization System Failure					
727 Z(Cj)					
737 Z(Cj)	1	0.29	0.14	0.14	
747 Z(Cj)					
727 R[1/flight]					
737 R[1/flight]	3.97E-08	1.15E-08	5.56E-09	5.56E-09	
737 R[1/flight]					
Technical/Mechanical Failure					
727 Z(Cj)	1	0.10	0.10	0.10	0.10
737 Z(Cj)	1	0.24	0.16	0.09	0.07
747 Z(Cj)	1	0.23	0.18	0.14	0.14
727 R[1/flight]	1.29E-07	1.29E-08	1.29E-08	1.29E-08	1.29E-08
737 R[1/flight]	3.52E-07	8.45E-08	5.63E-08	3.17E-08	2.46E-08
737 R[1/flight]	1.05E-06	2.38E-07	1.90E-07	1.43E-07	1.43E-07

Unknown Reasons					
727 Z(Cj)	1	0.75	0.75	0.5	0.5
737 Z(Cj)	1	0.72	0.7	0.67	0.43
747 Z(Cj)					
727 R[1/flight]	5.16E-08	3.87E-08	3.87E-08	2.58E-08	2.58E-08
737 R[1/flight]	3.06E-07	2.21E-07	2.15E-07	2.05E-07	1.32E-07
737 R[1/flight]					
Others					
727 Z(Cj)	1				
737 Z(Cj)	1	0.71	0.24	0.12	0.06
747 Z(Cj)	1				
727 R[1/flight]	5.16E-08				
737 R[1/flight]	9.65E-08	6.85E-08	2.32E-08	1.16E-08	5.79E-09
737 R[1/flight]	9.50E-08				
Total risk measure					
727 R[1/flight]	1.69E-06	8.64E-07	8.00E-07	6.32E-07	4.39E-07
737 R[1/flight]	3.05E-06	1.40E-06	8.27E-07	5.65E-07	2.45E-07
737 R[1/flight]	5.32E-06	2.13E-06	1.56E-06	1.45E-06	1.11E-06

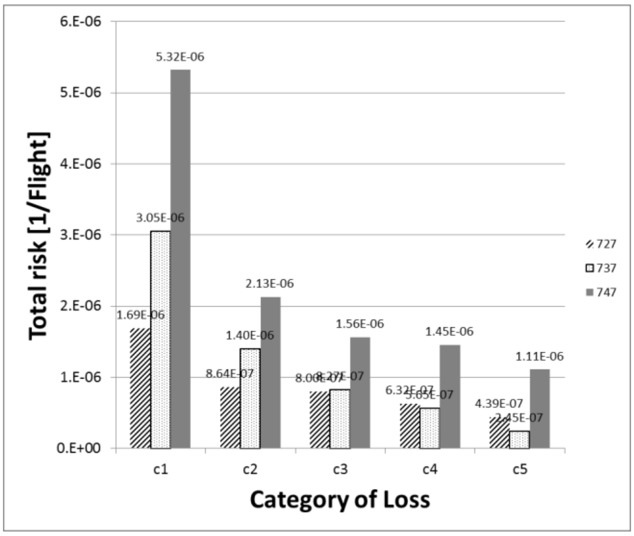

Figure 6. Total Risk for every category of loss per flight

6. Conclusion

The study of risk and reliability allows to observe the conditions under which the aircraft is flown have a significant impact on the level of risk. Difficult weather conditions significantly increase the likelihood of an accident (*Figure 4*) and lack of training or bad decision of the pilot have a large impact on safety (*Figure 3*).

Risk and reliability analysis within the aerospace industry highlights the fact that human beings are sometimes unable to take prompt decisions due to unwanted distractions within the vicinity of the environment him or her is working in. ICAO considers man to function in complicated system – SHELL (Software – Hardware – Environment – Liveware – Liveware) [2]. Most of the air accidents are results of poor performance or lack of coordination between the human and the machine that is influenced by the environmental conditions in which they operate. This might include the operations and the maintenance personal as well.

Not only, the study of risk and reliability has great importance in aircraft manufacturing but also in the investigations made by airlines with regards to delays, cancellations, and other issues. The research that has been carried out enables one to have detailed knowledge with regards to aircraft systems and aircraft component management for the purpose of inspection and planning of replacement.

This is the reason that aircraft manufacturers such as Boeing and Airbus implement risk and reliability analysis during the phases of new process design and also during the manufacturing of the finished product. This ensures safety and efficient operation of the flying machines. Hence it could be said, employing such strategy (risk and reliability analysis) has helped Boeing to reduce the total number of accidents by considerable margin.

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