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Designing and implementation of a fuzzy-dynamic model to evaluate system's risk and reliability

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Abstract. The purpose of this article is to permit the system safety and reliability analysts to evaluate the criticality or risk associated with item failure modes. The factors considered in traditional failure mode and effect analysis (FMEA) for risk assessment are frequency of occurrence (O), severity (S) and detectability (D) of an item failure mode. Because of the subjective, qualitative and dynamic nature of the information and to make the analysis more consistent and logical, an approach using fuzzy logic and system dynamics methodology is proposed.

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In the proposed approach, severity is replaced by dependency parameter then, these parameters are represented as members of a fuzzy set fuzzified by using appropriate membership functions and are evaluated in fuzzy inference engine, which makes use of well-defined rule base and fuzzy logic operations to determine the value of parameters related to system's transfer functions. The fuzzy conclusion is then defuzzified to get transfer function for risk and failure rate. The applicability of the proposed approach is investigated with the help of an illustrative case study from the automotive industry. The results provide an alternate solution to that obtained by the traditional method. The suggested assessment model was developed using toolbox platform of MATLAB 6.5 R.13.

Keywords: Failure modes and effects analysis; reliability management; systems and control theory; fuzzy logic; system dynamics approach.

1. Introduction

FMEA is an important technique that is used to identify and eliminate known or potential failures to enhance the reliability and safety of complex systems and is intended to provide information for making risk management decisions. In order to analyze a specific product or system, a cross-functional team should be established for carrying out FMEA first. The first step in FMEA is to identify all possible potential failure modes of the product or system by a session of systematic brainstorming. After that, critical analysis is performed on these failure modes taking into account the risk factors: occurrence (O), severity(S) and detection (D). The purpose of FMEA is to prioritize the failure modes of the product or system in order to assign the limited resources to the most serious risk items.

In general, the prioritization of failure modes for corrective actions is determined through the risk priority number (RPN), which is obtained by finding the multiplication of the O, S and D of a failure. That is RPN= OSD,

Where O is the probability of the failure, S is the severity of the failure, and D is the probability of not detecting the failure. For obtaining the RPN of a potential failure mode, the three risk factors are evaluated using the 10-point scale. The higher the RPN of a failure mode, the greater the risk is for product/system reliability. With respect to the scores of RPNs, the failure modes can be ranked and then proper actions will be preferentially taken on the high-risk failure modes. RPNs should be recalculated after the corrections to see whether the risks have gone down, and to check the efficiency of the corrective action for each failure mode. However, the conventional RPN method has been criticized extensively in the literature for a variety of reasons that can be found in next section. With respect to this review, the innovation of this study is more released.

2. Literature Review

FMEA, first developed as a formal design methodology in the 1960s by the aerospace industry (Bowles & pela'ez, 1995), has proven to be a useful and powerful tool in assessing potential failures and preventing them from occurring (Sankar & prabhu, 2001). FMEA is an analysis technique for defining, identifying and eliminating known and/or potential failures, problems, errors and so on from system, design, process and/or service before they reach the customer (Stamatis, 1995). When it is used for a criticality analysis, it is also referred to as failure mode, effects and criticality analysis (FMECA). The main objective of FMEA is to identify potential failure modes, evaluate the causes and effects of different component failure modes, and determine what could eliminate or reduce the chance of failure. The results of the analysis can help analysts to identify and correct the failure modes that have a detrimental effect on the system and improve its performance during the stages of design and production.

FMEA has been extensively used in a wide range of industries, including aerospace, automotive, nuclear, electronics, chemical, mechanical and medical technologies industries (Chang & Cheng, 2011; Chin, Wang, Poon & Yang, 2009b; Sharma, Kumar & Kumar, 2005).

Traditionally, criticality or risk assessment in FMEA is carried out by developing a risk priority number (RPN). Nevertheless, the crisp RPN method shows some important weaknesses when FMEA is applied in the real-world cases. The major shortcomings of FMEA are:

1-The relative importance among O, S and D is not taken in to consideration.

2-Different combinations of O, S and D may produce exactly the same value of RPN, but their hidden risk implications may be totally different.

3-The three risk factors are difficult to be precisely evaluated.

4-The mathematical formula for calculating RPN is questionable and debatable.

5-The conversion of scores is different for the three risk factors.

6-The RPN cannot be used to measure the effectiveness of corrective actions.

7-RPNs are not continuous with many holes.

8-Interdependencies among various failure modes and effects are not taken into account.

9-The mathematical form adopted for calculating the RPN is strongly sensitive to variations in risk factor evaluations.

10-The RPN elements have many duplicate numbers.

11-The RPN considers only three risk factors mainly in terms of safety.

Therefore, many alternative approaches have been suggested in the literature to resolve some of the shortcomings of the traditional RPN method and to implement FMEA into real world situations more efficiently. This section provides a review of those academic works attempting to deal with problems in the traditional RPN method and classify the existing literature by the approaches used. Furthermore, those articles that report on a method or technique that specifically aims at overcoming some of the drawbacks of the traditional FMEA. This implies that related articles merely describing the FMEA process or applying the traditional FMEA have not been included.

The methods used in the literature is divided into five main categories that the categories, each with their own related approaches and references, are reported in table 1. This review not only provides evidence that some alternate approaches are better than the traditional RPN approach, but also aids the researchers and risk analysts in applying the FMEA effectively. Nevertheless, time impact of causes on each other and dependency of causes to itself and or to others is neglected in the literature. On the other hand, results derived from applying FMEA directly effect on reliability, while this only theoretically is pointed by researchers and in practical scope has been not surveyed. Doing these as the most important problems in field of system reliability is challenging issue in this study.

Table 1. classification of risk evaluation methods in FMEA

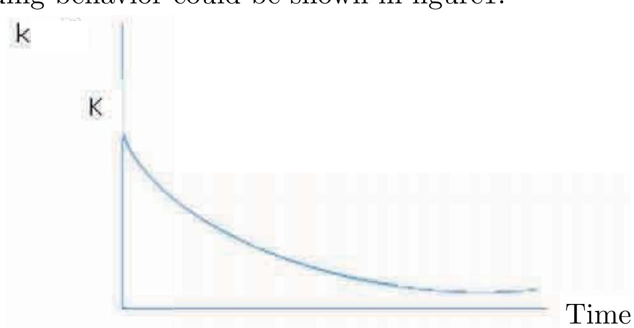
Categories	Approaches	Literature
MCDM	ME-MCDM Evidence theory AHP/ANP Fuzzy TOPSIS Grey theory DEMATEL Intuitionistic fuzzy set Ranking technique VIKOR	Franceschini and Galetto(2001) Chin et al.(2009b) Yang et al.(2011) Braglia et al.(2003b) Seyed-Hosseini et al.(2006) Chang et al.(2010) Liu et al.(2012)
Mathematical programming	Linear programming DEA/Fuzzy DEA	Wang et al.(2009b) Garcia et al.(2005)
Artificial intelligence	Rule-base system Fuzzy rule-base system Fuzzy ART algorithm Fuzzy cognitive map	Sankar and prabhu(2001) Bowles and pela`ez(1995),Guimaraes and Lapa(2004,2006,2007) Keskin and Zkan(2009) Pelaez and Bowles(1996)
Integrated approaches	Fuzzy AHP-Fuzzy rule-base system WLSM-MOI-partial ranking method OWGA operator-DEMATEL Fuzzy OWA operator-DEMATEL IFS-DEMATEL 2-tuple-OWA operator FER-Grey theory Fuzzy AHP-Fuzzy TOPSIS ISM-ANP-UPN	Abdelgawad and Fayek(2010) Zhang and Chu(2011) Chang(2009) Chang and Cheng(2011) Chang and Cheng(2010) Chang and Wen(2010) Liu et al.(2011) Kutlu and Ekmekcioglu(2012) Chen(2007)
Other approaches	Kano model Probability theory	Shahin (2004) Sant'Anna(2012)

3. Suggested methodology

The methodology used in this study is composed of two separable sections. The first section is related to estimate system's transfer functions and second section is about calculating its parameters. So, at following, these subjects are explained.

4. Estimation of Transfer Function (TF)

The problem of system's identifying is focused on determining its transfer function. TF is the operation that a system does on its inputs to receive output. If TF is determined, then output (system's response) with respect to various inputs by using of convolution integral and properties of laplace transform is obtained,$i.e. X(t) = \int_0^t U(\tau)G(t-\tau)d\tau = U(s)G(s)$. On the other words, if input is unit step and TF is determined at frequency domain then laplace transform of output will be: U(s) G(s) =X(s). Inverse laplace transform of above equation is equivalent with X (t).X(t) is system's step response and shows the state of system at every instant of time. In general, by observing output's behavior of a special system with respect to unit step input can be estimated its TF. For example, most of failure causes when increasing time is resulted in failures. So, risk change at start point (O) is maximum and when time increases it trends to zero (where failure is happened) such that, It's corresponding behavior could be shown in figure1.



Time

Figure 1: Time response of risk change, w.r.t time

Systems with such behavior (figure1) have TF in form of $G(s) = \frac{k\tau s}{1+\tau s}$

In $G(s)$, k is a parameter that represents velocity of cause's unit impact, τ is a parameter represents effecting time (equivalent with system's time constant) and s is laplace variable, $i.e.s = j + \sigma\omega$. Because of input is unit step and its laplace is $\frac{1}{s}$ so laplace transform of output is: $X(s) = \frac{1}{s}\frac{k\tau s}{1+\tau s} = \frac{k\tau}{1+\tau s}$.

Therefore, inverse laplace transform will be: $X(t) = ke^{-\frac{t}{\tau}}$
Normalized behavior is: $\frac{x(t)}{k} = e^{-\frac{t}{\tau}}$ so that, it's corresponding table is :

Table 2. Calculating states of the system

$\frac{t}{\tau}$	0	1	2	3	4	4.6	5	....	∞
$\frac{x(t)}{k}$	1	.368	.135	.05	.18	.01	.007	.....	0

It is concluded from table 2 that this type of systems at $\frac{t}{\tau} \geqslant 4/6$Cover 99 percent of their goal and is obtained steady state. This time is named settling time to one percent of steady state. So, time to failure (T) is assumed as: $T = 5\tau$

By the procedure similar to explained above, time response of failure rate is calculated. Transfer function for failure rate function is equivalent with:

$$G(s) = \frac{k\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

K is the average that system finally follows and is representing system's steady state response,$i.e.k = \frac{1}{T}$ such that $T = 5_\tau$
ζ Is damping ratio that is determined based on parameters of risk controlling signal obtained in previous stage ($k\&\tau$).

And ω_n is natural frequency of system that is equal with: $\omega_n = \frac{2\pi}{T}$
Parameters of above transfer functions are calculated by using fuzzy inference systems (FIS), so at following is explained.

5. Fuzzy Assessment Methodology

In this study is used three FIS. FIS 1 and FIS2 have similar inputs, i.e. O, D and Dependency. The output of FIS1 is K and for the FIS2 is ? that used to for risk's transfer function. In next stage K &? will be as inputs of FIS3 such that the output is ?. In every stage, inputs are fuzzified using appropriate membership functions to determine degree of membership in each input class. The resulting fuzzy inputs are evaluated in fuzzy inference engine, which makes use of well-defined rule base consisting of if-then rules and fuzzy logic operations to determine output level of the every FIS. The fuzzy conclusion is then defuzzified to get crisp values for outputs at various FIS, so that transfer functions related to quantities (risk and failure rate) can be evaluated accordingly. Finally, the unit step responses of the systems are calculated by using of convolution integral and properties of laplace transform explained in section 3-1. The fuzzy linguistic assessment model was developed using toolbox platform of MATLAB 6/5 R.13. To represent input and output variables in FIS graphically, triangular and trapezoidal membership functions (Figures2, 3 & 4) are used which are consistent with the definitions of the variables used in the study as depicted in tables3 -6.

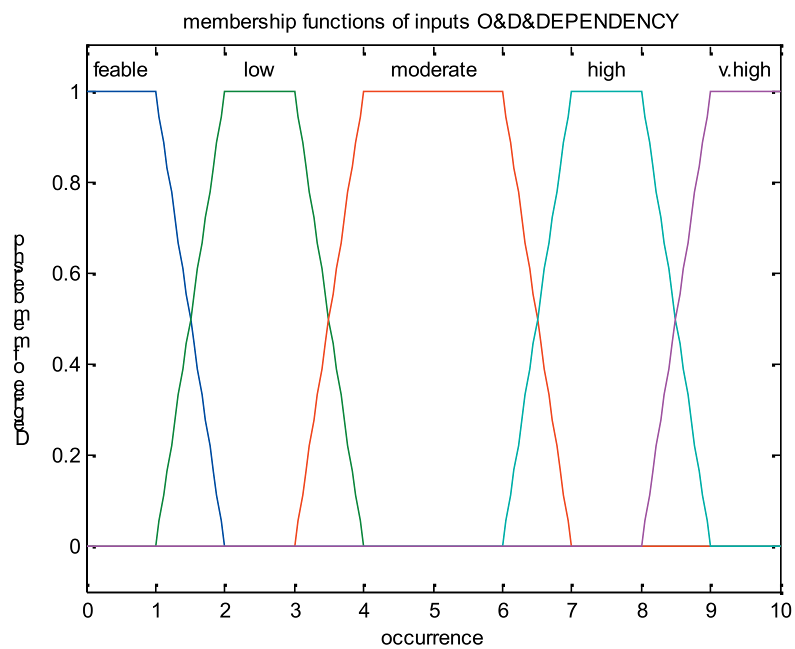


Figure 2: Fuzzy membership functions for inputs of FIS 1 & FIS 2

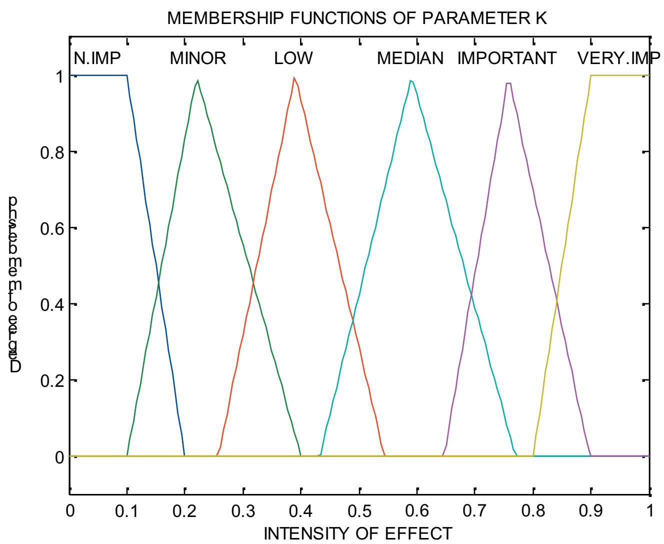


Figure 3: Fuzzy membership functions for outputs of FIS 1 & FIS 2

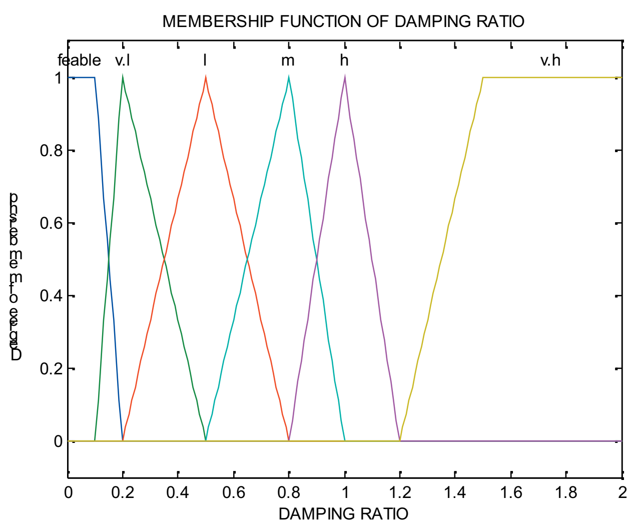


Figure 4: Fuzzy membership functions for output of FIS 3

The descriptive terms describing the dependency membership functions are Feeble, Low, Moderate, High and very high.

Table 3: Scales used to measure probability of failure occurrence

Descriptive assessmentof probability of failure	Mean time between failures	Score	Occurrence rate(%)
Feeble	>5 years	1	<0.01
Low	2-5 years	2-3	0.01- 0.1
Moderate	1-2 years	4-6	0.1-0.5
High	3-6 months	7-8	0.5 – 1
Very high	<3 months	9-10	>1

Table 4: Scales used to determine probability of non-detection

Non-detection	Score	Likelihood of non-detection (%)
Feeble	1	0 - 5
Low	2 3	6 - 15 16 - 25
Moderate	4 5 6	26 – 35 36 – 45 46 - 55
High	7 8 9	56 – 65 66 – 75 76 - 85
Very high	10	86 - 100

Table 5: Scales used for parameters k &? assessment

Rank no.	Effect on risk change (time & magnitude effect)	Meaning
0 - 0.1	Not Important	Less MTTR>1hour
0.11 – 0.25	Minor	MTTR >1day
0.26 – 0.5	Long	MTTR 1-4 days
0.51- 6	Median	MTTR4-8days
0.61 – 8	Important	External intervention for repairs
0.81 – 1	Very Important	Line shut down or production loss

Table 6: Scales used for damping ratio assessment

Descriptive assessment of Damping ratio	Time to failure	Score
V.L	Very short	0 – 0.2
L	Short	0.21 – 0.8
M	Median	0.81 – 1.4
V .H	Long	1.2/1 – 2

Case study

To demonstrate the application of proposed approach for carrying out suggested methodology, a case study from an industrial firm is proposed. There are many functional units in this case, while it is decided to conduct failure mode analysis of the main functioning unit i.e. piston's seat exfoliation operation. Two potential failure modes are released.

1- Increasing seat's diagonal and

2- Decreasing distance from piston's seat to piston's bottom. The cause of first mode is unregulated tool and for second is wobbling snip in system.

For the first cause input data is obtained: $O = 8, D = 9$ and Dependenc $y = 6$

For the second cause, data is obtained: $O = 5, D = 3$ and Dependenc $y = 4$

By using of two fuzzy inference systems, parameters of TF for the first cause will be $K = .768$ and $\tau = .24$. Also, parameters of TF for the second cause will be $K = .5$ and $\tau = .5$. The mapping of inputs to the outputs through the linguistic if-then rules adopted in the study is represented using a control surface plot (figure 5). Since in the study three inputs have been used, so the surface plot can be represented with a group of surfaces keeping one of the input variables stable. In this study one figure is shown for example. The rest of figures also have similar behaviors.

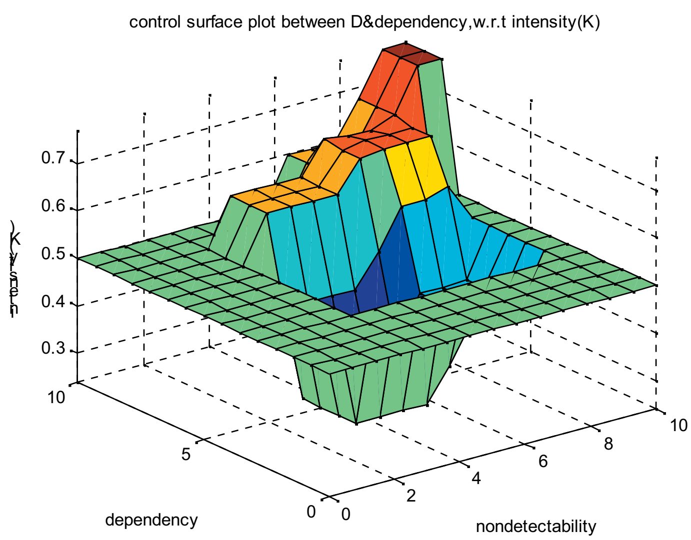


Figure 5: Control surface plot between (D) & (Dep), w.r.t K

These three-dimensional plots represent very well the systems used to in this study. Obtained values for $K\&\tau$ are used as the inputs of the third FIS. For the first cause is calculated $\zeta = .268$ and for the second cause $\zeta = .536$. Then, by using of the procedure detailed in the section 3-1 failure rate function for the first failure will be:

$$\lambda(t) = .831 - e^{-1.41t} cos5.04t + .28 sin5.04t$$

And for the second failure is:

$$\lambda(t) = .41 - e^{-1.34t} cos2.1t + .64 sin2.1t$$

The corresponding figures for calculated $\lambda(t)$ s is shown in figures 6, 7 respectively. It is pointed out that, this special case is composed of two failure modes, so failure rate for the corresponding operation is summation of two functions calculated before, i.e.

$$\lambda_s(t) = \lambda_1(t) + \lambda_2(t)$$

On the other hand, relation between failure rate and reliability functions is:

$$R(t) = e^{-\int_0^T \lambda(t)dt}$$

Therefore, in this case reliability is as shown in figure 8(-).

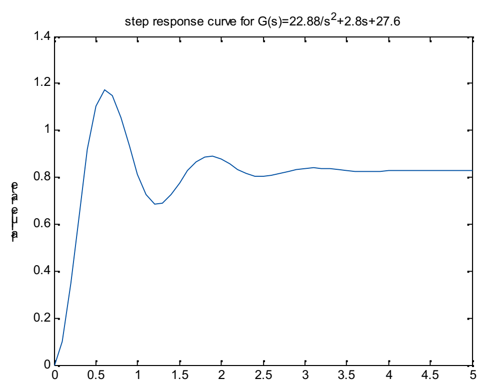


Figure 6: Failure rate function for the first failure

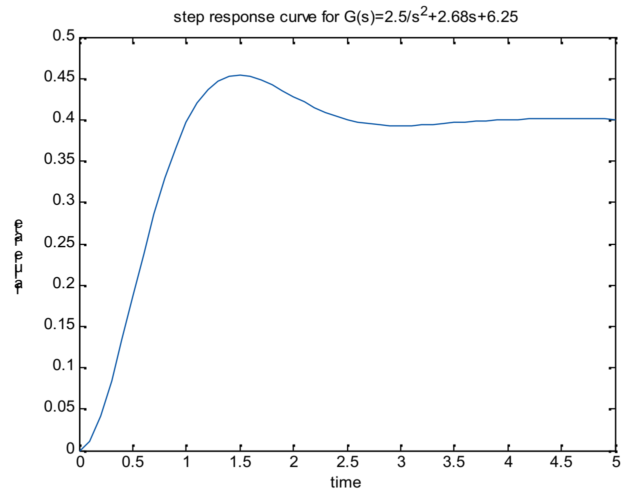


Figure 7: Failure rate function for the second failure

With respect to figures 6&7, because of lower settling time for the first cause, it was decided that first cause selected for corrective actions. Reliability after of correction is as shown in figure 8 by dashed line (-).

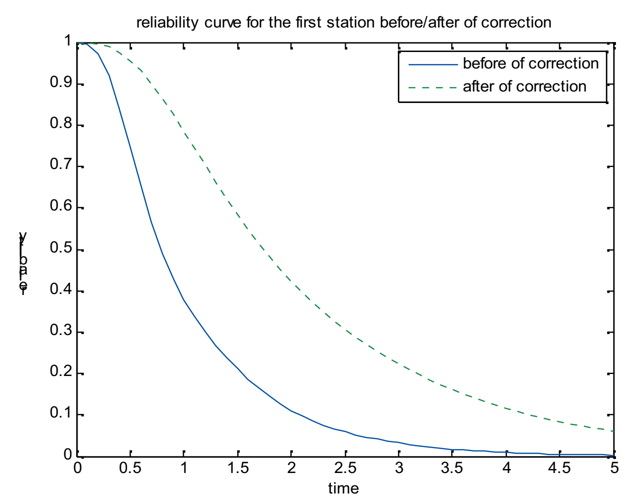


Figure 8: The impact of corrective action (feedback) on reliability

It is concluded from figure8 that in every instant of time reliability after correction is bigger than before correction. This is due to feedback factor in system.

6. Conclusions

It is concluded from this study that the uncertainty and static nature in the risk traditional assessment is solved using fuzzy-dynamic modeling. The use of fuzzy set approach and system's thinking confirm that how the fuzzy-dynamic assessment methodology in this study which makes use of membership functions, a well- defined fuzzy rule base, an inference system and convolution principle can enhance and improve the understanding of the dynamics of a complex problem in which decisions are to be made from imprecise, vague, subjective and dynamic information. Also this study shows that integrating of fuzzy logic-based approach and system dynamics methodology resolve the limitations associated with traditional method for RPN evaluation of failure causes in reliability analysis of system.

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