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Fuzzy Reliability Analysis of a Multi-Chiller System based on Modern Analytics

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Abstract: Cooling systems are important part of our day-to-day life in summer season. In cooling systems, most challenging part is to consume the less energy with longer reliability. A multi-chiller system is analyzed in the present work. In the present problem, a fuzzy logic-based approach is used to evaluate the fuzzy reliability of multi-chiller system. The reliability of a multi-chiller system depends upon the failure with the partial (part) loading ratio (PLR). PLR is taken as fuzzy parameter in this work. In this work we also compared the results of the approach Lagrangian Method (LGM), Genetic algorithm (GA) and Teaching learning-based optimization (TBLO) with our proposed approach.

Keywords: Fuzzy logic, Fuzzy failure rate, Partial load ratio (PLR), Multi-chiller system, Fuzzy reliability.

1. Introduction

A system is made up of many components or subsystems. Therefore, failure of any component or subsystem may lead to the system performance or its working capacity. Sometimes, system may be in completely fail state. The failure of systems affects the reliability. The reliability of systems is always being the topic of interest.There are many complex systems in various industry/factory, institutions and home appliances, which can be made more reliable using new methods/techniques.A chiller is responsible to remove heat from a liquid by absorption cycle or vapor compression. A chiller system is the main unit/part of our cooling systems like air conditioners and refrigerators. In multiple layered chiller system, there are two or more chillers are connected by series or parallel system. At the time of repair of one chiller in multiple chiller system the cooling requirement can be fulfilled by remaining units. So, such systems may be more reliable. Mathematical models for reliability estimation were discussed by Roberts[1] in engineering discipline. The concept of human reliability based on human nature/facts was presented by Dhillon[2] and the performance of chilled water systems which haven't enough thermal storage analysed by Bruan[3] using optimization techniques and the important parameters responsible for systems weaker performance was identified.The study of probabilistic reliability was given by Gnedenko[4] et al. To remove the uncertainties, exist in the data or parameters, fuzzy set theory was used and made the results free from existing errors. Zadeh[5] was the first person, who gave the concept of fuzzy logic. Fuzzy logic includes a function representing the uncertainty. This function is known as the membership function.Chang[6]used Lagrangian method to optimize chiller loading problem. Chang[7] et al. considered a chiller plant involving of several chillers as a substitute to progress efficiency during operation with merging the optimal sequence control. Yu[8] et al. considered that the use of high productivity chillers as an actualimpression to confirm the functioning performance of a chiller plant at higherstages.

Lisnianski[9] presented reliability assessment of multi-state systems and a chiller system analysed using Markov method. Particle swarm optimization (PSO) was applied by Lee and Lin[10] to optimize chiller loading including design, and different operating ways of air conditioning system. The comparison the results of differential evolution were done by Lee[11] et al. for equal loading distribution with latent growth model (LGM) and PSO. Usually, 40% of the whole energy is used up in heating, ventilation, and air conditioning (HVAC) systems and a chiller plant used the 50% of the total energy, which is responsible for the determining the energy performance of HVAC system[12].Esen[13] et al. present the optimal and robust design method considering uncertainty and reliability of a chiller plant.Most of the designers focus on the size of the chiller plant as well as larger cooling capacity in place of maximum cooling load to make sure that it could sufficiently work with cooling capacity to fulfil the demand under series of cooling load systemsand safety[14]. Peruzzi[15] et al. analysed the importance of reliability parameters considering the benefits of economic and environmental management. Chen[16] et al. used neural networks (NN) toanalyse the power feeding of the chiller system and used PSO method for optimal loading as well as saving energy. Cheng[17] et al. analysed the cooling load of a typical design based on simulation conferring to the statistic past climate circumstances and possible maximum boundaries. The performance of the conventional and optimal chiller design methods depends upon predefined conditions or closeness to these conditions but practically real problems are different from such situations due to the variation in parameters and component (part) failures. The teaching learning-based optimization (TLBO) method[18] was applied for optimization of multiple chillier systems. Cheng[19] et al. proposed a robust optimal design method and dealing with the system uncertainties and reliabilities. The result improved the sized pumping system's capability to provide the required cooling and operable under efficient region. Sharma and Pandey[20] obtained the profust reliability and profust availability of a three-unit degradable system by replacing the binary state assumption with fuzzy state assumption.Sharma[21] analysed the fuzzy reliability of an air conditioning system using the mean time to fuzzy failure rate with the help of fuzzy operators and required idle conditions (26°C dry bulb temperature and 63% relative humidity) for better performance of the system was considered. Yu[22] et al.applied chaotic estimation of distributionalgorithm optimal chiller loading. Jabari[23] et al. used imperialist competitive algorithm for energy saving in multi chillers systems. Dibavar et al[24]. proposed wild goat's algorithm to dispatch the multi chiller system.

The work done in this research paper is arranged in six sections. Section 2 is presenting some related basic definitions used in the presented study. Section 3 contains the methodology of this research work. Fuzzy failure (partial load) rate is also discussed and the algorithm of the proposed work has been given in section 4. We have also discussed the fuzzy reliability of the multi chillers system Numerical computations and the results are given in section 5. The conclusion and interpretation of the results of this work is discussed in the section 6.

2. Basic Definitions

Some related definitions are given below used in the present research work.

2.1. Fuzzy Set: A fuzzy set $\tilde{A}$ subset of a universal set U is important due to its membership function. Fuzzy set deals with the help of its membership function, which maps every member of the universal set into the unit interval [0,1]. Mathematically, a fuzzy set can be written as;

$$\tilde{A} = \{x, \mu_{\tilde{A}}(x) : x \in U\}$$

and membership function is given as; $\mu_{\tilde{A}}(x): U \to [0,1]$.

2.2. Chiller System:A chiller is a machine which helps to remove heat present in liquid by process of vapor compression and this cool liquid circulated through heat exchanger to cool air. In multiple chiller system more than one chiller unit are combined in series or parallel manner.

2.3. Cooling Load: The cooling load is the measurement of the heat which would require removing from a cooling space to control the temperature at a desired level. Cooling capacity means the ability of the cooling system of removing heat.

2.4. Partial Load Ratio (PLR): In view of a system through all-electric chilling, the finestprocess is accomplished when the power feeding of the system is lowest and the cooling load is fulfilled.PLR of a chiller can beexpressed by the following equation:

$$\mathrm{PLR} = \frac{\text{Chiller load}}{\text{Chiller capacity}}$$

3. Proposed Methodology

3.1. Teaching Learning Based Optimization (TLBO): Optimization is nothing but it is a process of finding the improved (optimal) value of an objective function. TLBO is also an optimization method. This method is based on the result of a teacher on the learners as output in the class. A teacher does hard work and teaches to students (learners) to be educated. After that student interacts with each other and discuss to explore/modify their knowledge, gained in the class. In this method (algorithm), the class (number of students) is assumed as population and subjects (number of subjects) as (decision) variable from which the students will gain knowledge through their teacher. This algorithm has two modes of learning as;

a) Teacher phase (students gain knowledge through teacher)

b) Learner phase (students improve knowledge through other students).

The flow chart of the TLBO algorithm is given in fig. I. The power each cooler consumes is an occupation of PLR of the cooler. At small loads, power feeding of outward chillers is largerdue to the motor losses. In a higher load, the input power risesbecause of thermal heat exchange incompetence. For a specified wet-bulb temperature, the power feeding of a motor chiller can be defined by the following equation:

$$\mu\tilde{P}_i = r_i + s_i\widetilde{PLR}_i + t_i\widetilde{PLR}_i^2 + u_i\widetilde{PLR}_i^3 \tag{3.1}$$

where $r_i,\ s_i,\ t_i$ and u_i coefficients of $\widetilde{PLR}$, which are also fuzzy.

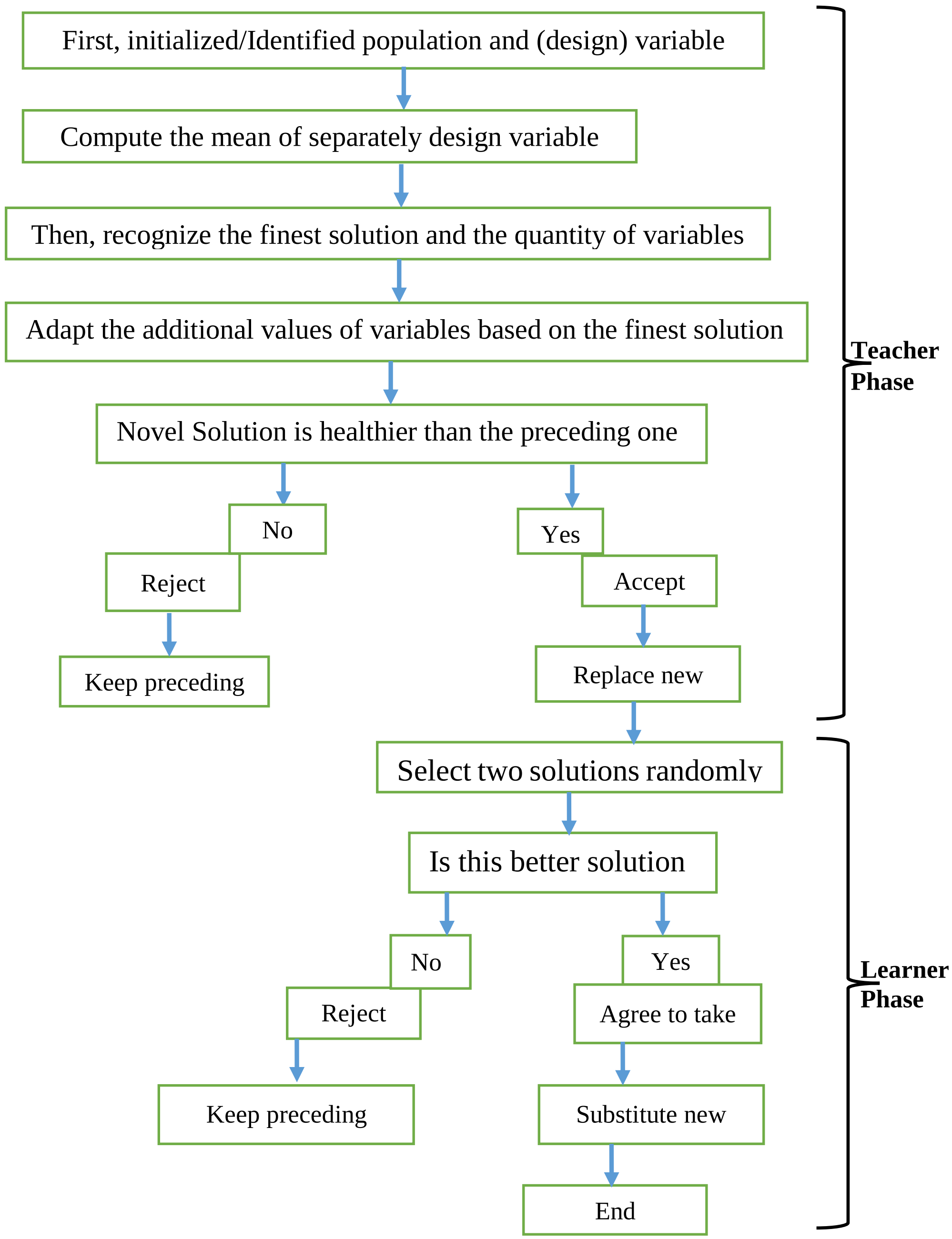


Figure 1: Flow Chart of TLBO

3.2. Lagrangian Method (LGM): A system (system of chillers) is said to be at superlative performance level, when the power feeding is minimum and the cooling (load) demand is fulfilled. Generally, PLR is the representator of cooling load and it is the ratio of the cooling load to design capacity of the chiller. The power consumption of the chiller systems can be reduced by controlling the water temperature that arrives in the condenser. If water temperature is low then power consumption is also minimum. For centrifugal chillers, the partial load power consumption rate is higher even at low loads due to motor losses and the rise in input power at high load is the effect of thermal heat exchange inefficiencies. Thus, the power consumption (P_i) of a motor chiller is convex occupation of its PLR (taking as fuzzy $\widetilde{PLR}$) at a given water temperature;

$$\mu\tilde{P}_i(kW) = r_i + s_i\widetilde{PLR_i} + t_i\widetilde{PLR_i^2} + u_i\widetilde{PLR_i^3} \tag{3.2}$$

where r_i, s_i, t_i and u_i coefficients of $\widetilde{PLR}$, which are fuzzy in nature. Coefficients and $\widetilde{PLR}$ both have fuzzy behaviour, therefore $\mu\tilde{P}_i$ is also fuzzy. In such problems, the chiller cooling output should remain within the operating limits of the objective function;

$$\text{Objective function } Z = Min\sum_{i=1}^{N}\mu\tilde{P}_i \tag{3.3}$$

Where, N is the number of chillers used for cooling and $\mu\tilde{P}_i$ is the power used up by the i^{th} chillers. The cooling load demand necessity be fulfilled by the constraint such as;

$$\widetilde{CL} = \sum_{i=1}^{N}\widetilde{PLR_i} \times \widetilde{RT_i} \tag{3.4}$$

$\widetilde{RT}$ is the capacity of the ith chiller.

The optimal solution of the present problem using Lagrangian method can be used and Lagrange multiplier $\tilde{\alpha}$ can be determined as;

$$\tilde{\alpha} = \frac{s_i + t_i\widetilde{PLR_i} + u_i\widetilde{PLR_i^2}}{\widetilde{RT_i}} \tag{3.5}$$

3.3. Genetic Algorithm (GA): Genetic algorithm is a good alternative for explaining constrained or unrestrained optimization problems. This method is based on Darwin’s theory of natural selection and it is able to mimicking biological evolution. This search algorithm was proposed by John Holland (1975). GA is able to digitalize the genetic evidence of an organism or we can say chromosome’s construction by coding the information into binary digits. Therefore, we use string of two numbers and which are 1’s and 0’s. By the evolution method, this algorithm is able to provide better offspring due to random selection of utmost favourable digit and thus, fragments from parents. Encoding process is the first step for solving the optimal chiller loading problems. In the encoding process variables are coded by binary system after that, binary codes are linked into strings of chromosomes. The variable quantity, needed to be handled are nothing but $\widetilde{PLR}$ if the chiller unit. After encoding the variables into chromosomes, the data produced into the chromosomes is the total $\widetilde{PLR}$ of the parallel units. For instance, if we have a system of three connected units and each unit has 10-digit binary codes to signify its $\widetilde{PLR}$. Then coding of three unitsforms a string (of chromosomes) and by initialization, these chromosomes become population. For instance, the binary code of a binary unit is $1011011010_2 = 730_{10}$, thus, binary code converted into decimal code to determine $\widetilde{PLR}$ and further, $\widetilde{PLR}$can be calculated as;

$$\widetilde{PLR} = 0.3 + 730 \times \frac{1 - 0.3}{2^{10} - 1} (\widetilde{PLR}\text{lies between 0.3 and 1})$$

Similar process used for other units to calculate $\widetilde{PLR}$. After decoding of every chromosome to chiller unit's $\widetilde{PLR}$, objective function is used to calculate the related result in this process. In power systems, it is desirable to minimize the power consumption and it can be written as;

(3.6) Objective function $= Min \sum_{i=1}^{N} \mu \tilde{P}_i, i = 1,2, \dots N$ (number of chillers),

and

(3.7) $$ER = \sum_{i=1}^{N} \widetilde{PLR_i} \times \widetilde{RT_i} - \widetilde{CL}$$

Where, ER is the discrepancy. The capacity requirement has been satisfied means result of the previous equation becomes zero.
Next step is the normalization, which is as follows;

(3.8) $$\%OF = \frac{OF_S - OF_{min}}{OF_{max} - OF_{min}}$$

and

(3.9) $$\%ER = \frac{ER_S - ER_{min}}{ER_{max} - ER_{min}}$$

Here $\% \, OF$ represents the "percentage rate" of the objective function when string has normalized.$OF_S$is the corresponding worth of the objective function and $OF_{min}(OF_{max})$ is the minimum (maximum) value of the objective function in the population. Similarly, $\% \, ER$ is the "discrepancy percentage" of the string after normalization. ER_S represents the discrepancy of constraints of the string and ER_{min} (ER_{max}) represents the minimum (maximum) discrepancy of the restrictions in the population.
Next step is the fitness function. This step is based on the normalization. The value of the fitness function can be minimized as the minimized valued of the previous step are desirable. The fitness function can be written as;

$$\min Fitness = \min(\%OF + \%ER) \tag{3.10}$$

Fitness function's value decides the quality of the chromosome. It means power consumption is low if min fitness is smaller.
Now, the reliability of the chiller system can be determined as follows;

PLR Failure (load) rateλ = 1- $\frac{\text{Chiller load}}{\text{Design capacity}}$

Fuzzy failure (load) rate $\tilde{\lambda}$=1- $\frac{\text{Fuzzy Chiller load}}{\text{Design capacity}}$

Fuzzy Reliability of power consuming system is given by

$$R_{PCS} = e^{-\tilde{\lambda}t}$$

4. Algorithm for the Proposed Work

In the present research work fuzzy reliability of the multi chiller system is focused. The cooling capacity of any system depends upon its chillers reliability. If part failure load ratio is appeared during operation, then reliability of the chiller is affected. If the failure is high then reliability of the system decreases. The algorithm of the proposed work as fellow:

Step 1: Firstly, PLR using different techniques are determined.

Step 2: The data of the step 1 is changed into the triangular fuzzy numbers.

Step 3: After fuzzifying the data of the first step, fuzzy failure (load) rate is calculated.

Step 4: Fuzzy failure (load) rate $\tilde{\lambda}$=1- $\frac{\text{Fuzzy Chiller load}}{\text{Design capacity}}$, using the formula fuzzy failure rate is obtained.

Step 5: Results of the previous step is defuzzified.

Step 6: Results obtained in the step 5 are used to calculate the fuzzy reliability.

Step 7: With the help of the results of the previous step, a comparison is made for the fuzzy reliability of the multi chiller system.

5. Numerical Computations

The values in the table I are presenting the coefficients values in the PLR curve and bold values are crisp. Each value is presenting a triangular fuzzy number. Defuzzified values of each chiller are given corresponding to chiller 1,2 and 3.

Table I. Presenting the coefficient of PLR curve

Chillers	r_i	s_i	t_i	u_i	**Defuzzified values**
CH-1.	(100.55, **100.95**, 101.15)	(818.41, **818.61**, 818.81)	(-973.03, **-973.43**, -973.63)	(788.55, **788.55**, 788.55)	100.85, 818.51, -973.33, 788.45
CH-2.	(66.198, **66.598**, 66.798)	(605.94, **606.34,** 606.54)	(-380.18, **-380.58**, -380.78)	(275.55, **275.95**, 276.25)	66.49, 606.24, -380.48, 275.85
CH-3.	(129.69, **130.09**, 130.29)	(304.10, **304.50**, 304.70)	(13.977, **14.377**, 14.577)	(99.4, **99.8**, 100)	129.99, 304.40, 14.277, 99.70

The numerical computations of the present research work are shown in the table I. The comparison of outcomes of LGM, GA and TLBO are given.

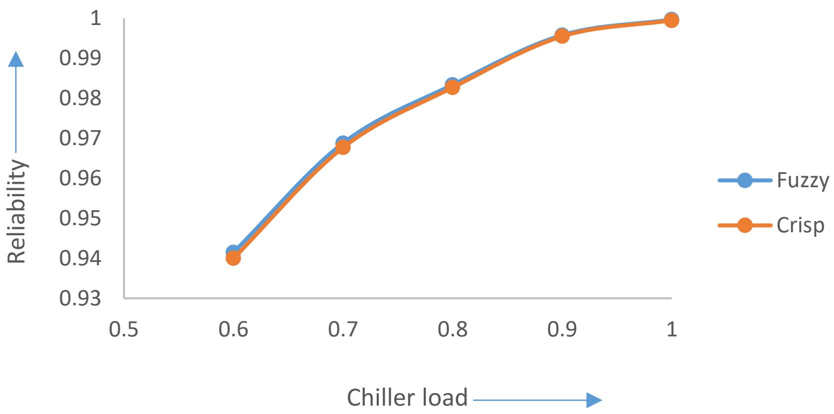
Table II. Comparisonof numerical results of three different techniques

Cooling load	No. of chillers	LGM		GA		TLBO	
		PFFLR	R	PFFLR	R	PFFLR	R
90%	1	0.265	1 **1**	0.185	0.9999 **0.9995**	0.274	1 **1**
	2	0.025		0.065		0.025	
	3	0.0		0.035		0.0	
80%	1	0.335	0.996 **0.9957**	0.295	0.9959 **0.9955**	0.340	0.9959 **0.9957**
	2	0.135		0.195		0.141	
	3	0.115		0.095		0.117	
70%	1	0.35	0.987 **0.9844**	0.305	0.983 **0.9827**	0.403	0.9839 **0.9837**
	2	0.245		0.315		0.255	
	3	0.235		0.265		0.241	
60%	1	0.465	0.965 **0.9649**	0.475	0.968 **0.9677**	0.465	0.965 **0.9642**
	2	0.375		0.255		0.384	
	3	0.345		0.455		0.345	
50%	1			0.505	0.941 **0.94**	0.506	0.9419 **0.9416**
	2			0.555		0.614	
	3			0.425		0.383	

PFFLR: Partial fuzzy failure rate, **R:** Reliability
In table II, the dark values represent the crisp values for reliability.

6. Conclusion

In complex systems reliability is the main topic of interest. In chiller systems failure (of partial load) rate is the main cause of loss of reliability. Multi chiller systems are reliable because any single unit is under maintenance then other unit can provide the required cooling load.



FigureII. Presentation of fuzzy reliability for the system of chillers for GA

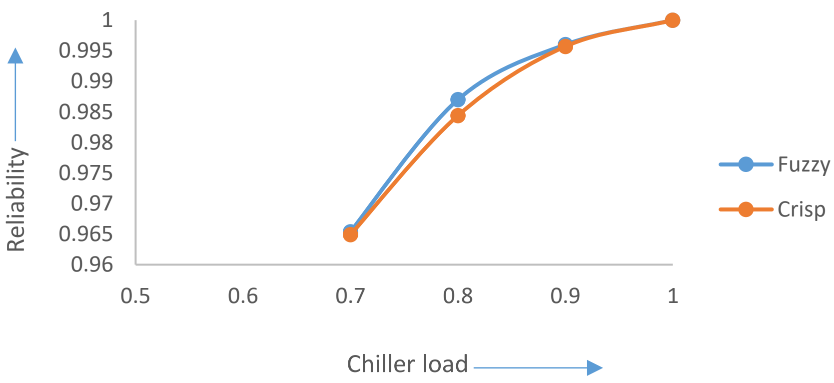


Figure III. Presentation of fuzzy reliability for the system of chillers for LGM

The results of the fuzzy reliability of the multi chiller system are graphically presented in the figure II, III and IV. It is well known that the fuzzy approach is superior than conventional approach. So, this method is efficient to cover the uncertainty in the traditional method. This is clear from the figures II-IV, when chiller load is increased then fuzzy reliability tends towards higher level. So, this method is more suitable to get more reliability.

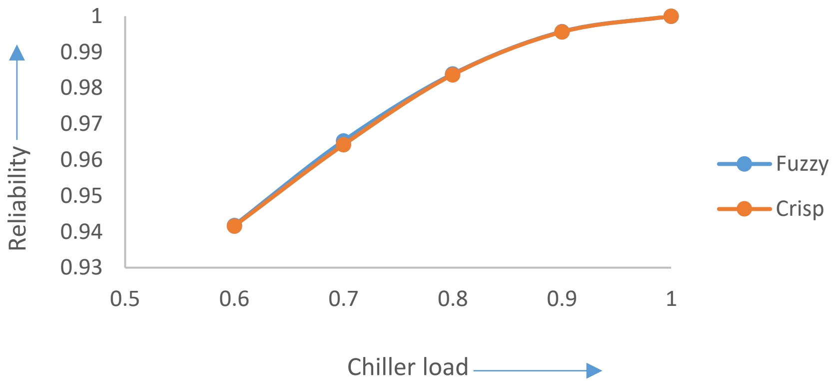


Figure IV. Presentation of fuzzy reliability for the system of chillers for TLBO

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