Research on Reliability Modeling, Allocation and Prediction of Chemical Production System

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Abstract. Reliability allocation and prediction play an important role in the chemical production system, controlling the significance of each production allocation and predicting system reliability to analyze the designs in each system or integrated system if meeting requirements or not. This paper takes an ethylene plant as an example to study reliability modeling, allocation and prediction of related system. It is aimed to allocate and predict each production system or unit. In terms of system reliability allocation, it finds out the reliability allocation R in integrated system is 0.76460 with improved fuzzy analytic hierarchy process (AHP). Due to the number higher than initial reliability value of 0.73886, it illustrates the integrated reliability allocation meets the design requirements. In terms of reliability prediction, the result is more accurate when using Bayes fuzzy reliability prediction to calculate system reliability level and it can reflect this kind of indeterminate small sample data better.

1 Introduction

With the continuous development of science and technology, the manufacturing technique of chemical enterprises is increasingly complex, the technology is more and more consummate and the equipment becomes various. Besides, the products on a large scale are inflammable, explosive, poisonous and detrimental while the productive process is continuous. Therefore, the reliability analysis is beneficial to the production systems with safer, more stable and continuous running.

With the continuous development of systems engineering technology, reliability theory originally used in electronic field is also gradually applied in other fields. Limin Gao et al. use weighting coefficient method to improve proportional scaling in Analytic Hierarchy Process for more practical results. Then they combine the method with AHP again to make allocation and find it functional and reasonable (Limin, Gao., Kai, Wu., &Yu, Sun., 2014). Yingkui Gu improves evaluation methodology with triangular fuzzy number to increase fuzzy comprehensive evaluation as perfection, which is beneficial to analyze the reliability allocation of engines (Yingkui, Gu., &Kaiqi, Huang., 2009). Li Du and Aiqin Jia et al. introduce comprehensive judgment with multipolar fuzzy form into reliability allocation (Li, Du., Hongzhong, Huang., &Wei, Song., 2009 & Aiqin, Jia., &Jianjun, Chen., 2010). Dezi Zhao implements reliability prediction with comprehensive judgment with fuzzy form based on trapezoid fuzzy number and carries out fuzzy allocation with reliability form by referring to the allocation method with proportion portfolio form (Dezi, Zhao., Weidong, Wen., &Chengmei, Duan., 2005).

2 Overview reliability of production system

2.1 Connotation of production system reliability

In terms of production system, its connotation of reliability is different from that of products and equipment. Compared with the mechanical system, the difference of production system shows that its cache region can partly “protect” mobility phenomenon existed in production. Once the device breaks down and doesn’t work on the rails, the products and safe stock temporarily stored in its cache region will provide subsequent devices to process products in time and recover regular production. The production mobility won’t be broken if it doesn’t completely consume away the capacity in cache region before the device being repaired and the system is still reliable. Otherwise, the mobility will be broken and the production will break off while the system loses its utility.

2.2 The necessity of studying on production system reliability

To determine scientific and rational production plan for efficient management, it has very important practical significance to study chemical production system reliability. In the specific productive process, it usually leads to production halts due to unexpected factors like equipment failure, unreasonable production plan, raw materials in short supply and other human factors. So it is necessary to develop research on production system reliability to avoid these problems as far as possible. It is much easier to cause biased assessment results if it judges the true level of integrated system reliability only in accordance with mechanical failure in production system. To make the predicted value consistent with reality, it should distinguish reliability problems between production system and mechanical device and consider structural features of production system and its all subsystems to analyze production system reliability with mentioned research methods.

3 Research on reliability modeling and allocation of production system

3.1 Method selection of modeling and allocation of production system reliability

When analyzing production system reliability, it often appears many varieties of uncertain factors affecting performance. The research is only based on experience or analogous data because designing system is short of accurate and reliable data. The inefficient data of production system is always caused with human factors, statistical approaches or other unexpected and inevitable factors. So the production system is indeterminate. Most scholars choose methods on the basis of fuzzy theory to study production system reliability and perform further research on some inefficient data unable to be collected exactly.

3.1.1 Fuzzy analytic hierarchy process

Fuzzy analytic hierarchy process (FAHP) is a kind of analytical method combining analytic hierarchy process and fuzzy mathematics with more indeterminacy and complexity of objects, which is more reliable to achieve research results. It studies different complex problems and gets good effect with fuzzy evaluation and analytic hierarchy process. During the hierarchy process, it should take system layers of different types of indexes into sufficient consideration and choose FAHP to analyze various factors with weight determination and comprehensive assessment.

3.1.2 Improved FAHP

Use Based on Analytic Hierarchy Process, FAHP combines related theories of fuzzy mathematics to solve one-sided problems in assessment results due to individual preference efficiently. However, it is necessary to conduct conformance testing for fuzzy judgment about correlation matrix. Aimed at these problems, this paper improves FAHP to form improved fuzzy analytic hierarchy process (IFAHP) (Youqun, Zhao., &Yingjie, Liu., 2013.), which solves the difficult problem successfully. Compared with FAHP, this method builds corresponding judgment matrix with three scales. They can be transformed to become fuzzy consistency form. Therefore, the simple scale setting is also in accordance with the grades of fuzzy assessment without conformance testing.

The specific building steps are following:

(1)Build hierarchical structure. This method has familiar analytical steps with FAHP. It need classify objects and builds structural hierarchy of each factor, including index level, criterion level and objective level.
(2)Build judgment matrix with scales. IFAHP is a little different from FAHP so the scale selection also has relevant difference. IFAHP is defined with three scales as shown in table 1.

Table 1. IFAHP judging scale and meaning

Scale	Meaning
0	Compared with two indexes, j is more important than i
0.5	Compared with two indexes, i is as important as i
1	Compared with two indexes, i is more important than j

The simple index definition with scales is helpful for experts to achieve clear and correct conclusions when judging. With the fuzzy definition of some factors or indexes, it is beneficial to find out which index is more important from the two and complete the exact analysis.

(3) Perform weight calculation. W is principal index, Wi is derivative index, evaluation index in each level is Vi. Weight calculation is conducted on scale scheduling of objective level. Two parts are calculated as follow:

Calculation of evaluation domain in each level：

$$V_i=\sqrt[n]{\prod_{j=1}^{n} a_{ij}};$$

For each weight calculation, $W_i=V_i\Big/\sum_{i=1}^{n}V_i$;

Comprehensive weight vector is W=（W_1，W_2，…W_i）,where（i=1,2,3,…,n）.

（4）Allocation of reliability system index. It need allocate weight with failure rate to perform the allocation of reliability system index rather than directly performing it. We calculate it with comprehensive weight (W) in objective level, each system weight (W_i) in index level and failure rate (λ_i)The specific formula is shown:

$$\lambda_i=\lambda\cdot\frac{1}{w_i}\Big/\sum_{i=1}^{n}\frac{1}{w_i}$$

Then reliability index is $R_i=1-\lambda_i$

This method decreases calculating iterations as far as possible and meets the accuracy of operation in fast speed without conformance testing.

3.2 IFAHP applied to the research on allocation of chemical production system reliability

Chemical production system is composed of complex subsystem with many stages so its reliability allocation is the same with it. One system reliability can’t be analyzed alone to replace integrated system reliability. With the higher requirement of clients for exact matching and performance ratio of products, enterprises not only meet clients' requirements but take production cost into consideration. Under various external factors, it becomes an important research issue to find out how to realize reliability allocation in each system well (Shilong, Li., 2013). According to IFAHP, this paper builds a model.

(1)Build subsystem in index level. Based on actual running characteristics of chemical production system, it divides into objective level, criterion level and index level. Each index in criterion level(B) contains 5 factors in index level(C). C1-C5 means reactor, pump, compressor system, mechanical equipment system, dynamical system and thermal system, respectively. The criterion level includes 6 levels of degree of importance, difficulty of repairing, work environment, technological level, expense dexterity and structural complexity. The specific information is shown in table 2.

Table 2. Build indexes of chemical production system

objective level(A)	criterion level(B)	index level©
chemical production system(A)	Degree of importance(B1)	C1-C5
	Difficulty of repairing(B2)	C1-C5
	Work environment(B3)	C1-C5
	Technological level(B4)	C1-C5
	Expense dexterity(B5)	C1-C5
	Structural complexity(B6)	C1-C5

(2)Data acquisition. Choose relevant experts to evaluate for original data. Evaluate each index after confirming system levels. We should select experts famous in this field, such as senior engineer or technicist and department manager. They have a strong understanding of effects on system reliability and make quantifying evaluation on each index. Summarize all assessment results from experts to get relevant sample data.

(3)Weight calculation. Weight calculation is performed at above data. Calculate subsystem in index level and weight sequencing to confirm comprehensive weight.

(4)Allocation of system reliability. Calculate formulas with IFAHP and allocate failure rate and reliability into subsystem for reliability in each system.

3.3 Case analysis

3.3.1 Overview of cases

Petrochemical branch company in Dushanzi area (hereinafter referred to as Du petrifaction) is subordinate to Chinese Petroleum Company. This enterprise mainly engages in integration production of large-scale refinery industry and chemical engineering industry. With the reform and development, it makes strategic adjustment, planning and implementation. Du petrifaction has become a comprehensive enterprise with integration of oil refining and chemical engineering, whose property has increased one billion and working ability has improved a lot. There are not only refinery, ethylene plant and thermal power plant at this stage but multiple sets of refining equipment and devices related with ethylene and relatively perfect infrastructures.

3.3.2 Research on reliability allocation of cases

The heading With expert evaluation of the selected criterion level and objective level, it concludes the assessment results with judgment matrix for final weight calculation.

(1) Calculation is performed using weight in criterion level, which has great effect on objective level through precedence matrix. According to expert assessment results, this paper weighs the impact analysis. As a whole, the weight sequencing is $B_3>B_2>B_1>B_5>B_4>B_6$. Then build precedence matrix(F_{BA})on the basis of this sequence.

$$F_{BA}=\begin{bmatrix} 0.5 & 1 & 0 & 1 & 1 & 1 \\ 0 & 0.5 & 0 & 1 & 1 & 1 \\ 1 & 0 & 0.5 & 1 & 1 & 1 \\ 0 & 1 & 0 & 0.5 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0.5 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0.5 \end{bmatrix}$$

By summing and transforming precedence matrix, it finally figures out the weight matrix of criterion level （B）on objective level（A）.

W_{BA}=(0.2167，0.1833，0.2500，0.1500，0.1167，0.0833)

(2) Perform weight calculation at indexes of criterion level and order indexes by scoring weight, introducing precedence matrix to sum and transform for scores.

The ordering result of each index in criterion level: B_1：$C_1>C_4>C_2>C_3>C_5$；B_2：$C_5>C_1>C_4>C_2>C_3$；B_3：$C_2>C_1>C_3>C_4>C_5$；B_4：$C_1>C_4>C_5>C_2>C_3$；B_5：$C_3>C_2>C_1>C_4>C_5$；B_6：$C_1>C_5>C_4>C_2>C_3$；

Build precedence matrix（F_{CB}）：

$$F_{CB1}=\begin{bmatrix} 0.5 & 1 & 1 & 1 & 1 \\ 0 & 0.5 & 1 & 0 & 1 \\ 0 & 0 & 0.5 & 0 & 1 \\ 0 & 1 & 1 & 0.5 & 1 \\ 0 & 0 & 0 & 0 & 0.5 \end{bmatrix}$$

$$\vdots$$

$$F_{CB6}=\begin{bmatrix} 0.5 & 1 & 1 & 1 & 1 \\ 0 & 0.5 & 1 & 0 & 0 \\ 0 & 0 & 0.5 & 0 & 0 \\ 0 & 1 & 1 & 0.5 & 0 \\ 0 & 1 & 1 & 1 & 0.5 \end{bmatrix}$$

Calculate weight matrix by summing and transforming precedence matrix and the final results are shown as follow:

V_{CB1}=（0.2，0.1，0.25，0.15，0.3）^{T};
V_{CB2}=（0.2，0.3，0.15，0.25，0.1）^{T};
V_{CB3}=（0.25，0.15，0.2，0.3，0.1）^{T};

V_{CB4}=（0.15，0.25，0.2，0.1，0.3）^{T};
V_{CB5}=（0.3，0.15，0.25，0.1，0.2）^{T};
V_{CB6}=（0.3，0.15，0.25，0.1，0.2）^{T}

Transform above vectors into matrix:

$$V=\begin{bmatrix} 0.2 & 0.2 & 0.25 & 0.15 & 0.3 & 0.3 \\ 0.1 & 0.3 & 0.15 & 0.25 & 0.15 & 0.15 \\ 0.25 & 0.15 & 0.2 & 0.2 & 0.25 & 0.25 \\ 0.15 & 0.25 & 0.3 & 0.1 & 0.1 & 0.1 \\ 0.3 & 0.1 & 0.1 & 0.3 & 0.2 & 0.2 \end{bmatrix}$$

In conclusion, the result of weight calculation is
$W=W_{BA}V$=(0.2190, 0.1911, 0.1550, 0.1832, 0.2535)

(3) Calculate reliability with weight scores. The first step is to calculate failure rate. Calculate index level with formulas. Data is shown as follow:

λ_{C1}=0.05326；λ_{C2}=0.04636；λ_{C3}=0.06557；
λ_{C4}=0.04025；λ_{C5}=0.05569

Then reliability is

R_{C1}=0.94674；R_{C2}=0.95364；R_{C3}=0.93443；
R_{C4}=0.95975；R_{C5}=0.94431

So overall reliability after system allocation is:

$$R=\prod_{i=1}^{n} R_{Ci}=0.76460$$

The initial reliability of chemical production system is 0.73886. We can find that the current reliability allocation meets design requirements. Specifically, it is a complex structural system and difficult to repair when smoothly running pumps and compressor system with high reliability allocation. The reliability of reactors is higher, which is related with its importance. The failure rate of separator, filter and vibrator included in mechanical system is at Intermediate level of allocation and much lower than the first two types. The stability of thermal and dynamical system is relatively higher but the reliability is the lowest in 5 types of systems.

4 Reliability prediction of production system

4.1 Method selection of reliability prediction of production system

The reliability prediction of production system is aimed to estimate its reliability quantitatively during production design. The sectional reliability levels of each production unit and integrated production system are evaluated in accordance with historical reliability data and specialist experience of each unit (or each subsystem), characteristic of system structure and actual working conditions (Weili, Wang., 2014).

A distinguished scholar from English T. Bayes put forward Bayes formula and relevant inductive reasoning, following with the true Bayesian estimate for statistical inference on systems. When using Bayes estimation, it gets prior distribution in advance and confirms posteriori distribution later. If each unit shows independent failure and its reliability is replaced by random variable, it will confirm posteriori distribution of this system using Bayes theorem and prior distribution of subsystems and achieve posteriori distribution of integrated system reliability. Therefore, system reliability variables can become unique and random with Merlin integral-transform method. The random variable is dead time when calculating system reliability with fuzzy Bayes theorem. But the dead time actually collected may be uncertain due to various influencing factors, it is better to perform analysis with fuzzy sets.

Because of mutually independent index unit in systems, subsystem reliability R_i constitutes that of integrated system. Then the formula is $R=\prod_{i=1}^{n} R_i$

In a hypothesis of chemical production system, x_i is independent random variable, probability density function (pdf) is f_i, then a posteriori distribution formula of production system is

$$M(g_i;u)=\prod_{i=1}^{k} M(f_i;u)$$

Then

$$r=E[R/m,v]=\prod_{i=1}^{k}\left(\frac{v_i+\theta_i}{v_i+\theta_i+t}\right)^{m_i+\theta_i}$$

Where m is ineffective amount; t is total observation time; vi is specific observation time; u 、θ are gamma distribution parameters.

Estimate fuzzy Bayes point with this expression and find out failure counts among test time to perform statistic analysis on existing data. This method is very appropriate for small sample data and easy to achieve exact system reliability prediction in uncertain situation.

4.2 Case analysis

4.2.1 Overview of case

The reliability prediction is based on maintenance (Sriramdas, V., Chaturvedi, S. K., &Gargama, H., 2014). It is used to decrease equipment failure, enhancing system stability and reducing running cost. It takes centrifugal pump system of cracking unit from Du petrifaction ethylene plant as an example to perform analysis. This paper selects several specific pumps to predict because the selected part is construction in process. The results are shown in table 3.

Table 3. The common faults and repair cycle of specific pumps

No.	Name	Common fault	Repair cycle
1	Charging pump	Seal failure	10 months
2	Circulating pump	Seal and impeller corrosion failure	10 months
3	Splitting fuel pump	Seal failure	10 months
4	Reflux pump	Seal failure	10 months
5	Delivery pump	Seal and impeller corrosion failure	10 months
6	Bleeding pump	Seal failure	10 months

4.2.2 Reliability Prediction

Table 4. Reliability prediction values of each index unit in production system(8h)

Device name	Device number	Equipment failure rate	Device reliability
Charging pump	1	0.00535	0.99465
Circulating pump	2	0.00371	0.99629
Splitting fuel pump	1	0.00801	0.99199
Reflux pump	3	0.00311	0.99689
Delivery pump	2	0.00421	0.99579
Bleeding pump	1	0.00587	0.99413

According to reliability prediction（8h）of each centrifugal pump system unit in cracking plant, we can predict its reliability level in 8h (Refer to chart 4). Due to construction in process, there is no failure or failure data in each production unit. So we only can refer to former data without true sample information. Therefore, fuzzy Bayes method is useful for reliability prediction of some uncertain sample data and efficient to analyze system reliability with fuzzy data.

5 Conclusions

There is some differences among the reliability allocation of chemical production system because the different importance of each index or unit. Based on the analysis of ethylene production system in this paper, the reliability allocation is relatively high in pumps, compressors and reactors systems. As a whole, the reliability allocation R in integrated system is 0.76460, higher than initial reliability value of 0.73886, so it illustrates the integrated reliability allocation meets the design requirements. The weight of reliability allocation calculated with IFAHP is identical with the physical truth, not only including failure conditions in chemical production system but expected design inference. Therefore, it has great application value for reliability modeling and allocation of chemical production system.

This paper is aimed at relevant researches on reliability theory of chemical production system to discuss modeling and prediction methods. Modeling is the prerequisite of reliability theory to perform design so it is necessary to build matched models for production system and the prediction process of that is not from down to up but from the part to the whole. Besides, reliability prediction is also the significant basis of allocation and working. With reliability prediction of each centrifugal pump system unit in ethylene cracking plant, we predict the system reliability level in 8h with fuzzy Bayes method. The result is relatively exact and this method is appropriate to predict the reliability of uncertain sample data with good reflecting level.

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