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A Novel Reliability Evaluation Method Based on RBD and AHP for Industrial Network Systems

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Abstract. Since each component has different impacts on reliability of the industrial network system, a multi-layer reliability evaluation method was proposed in this paper. Firstly, in order to construct multi-layer reliability evaluation system, a framework of industrial network system was introduced based on analytic hierarchy process (AHP). Secondly, a multi-layer reliability evaluation model with weight coefficient of components was proposed based on reliability block diagram (RBD). Thirdly, the simple rule-based fuzzy judgment and risk priority number (RPN) were applied to determining weight coefficient. Last, a reliability evaluation case of the industrial network system for an electronic automatic assembly line was studied. It shows that the proposed method is more reasonable than the conventional reliability analysis method, and the reliability prediction result is consistent with the engineering practice.

1 Introduction

Reliability has become a common problem of industrial network system, and its indicator is considered as an important quality attribute, which has the same important status as technical and economic indicators such as system performance and cost. With the development of reliability engineering, the idea that reliability of product is the result of design, manufacture and management has been understood and accepted gradually. According to statistics, around 80% of the product reliability problems derive from the design stage of product, which means the design level directly influences the product reliability in practice. So, safety, reliability and efficiency of industrial network system depend on system reliability analysis, assessment, prediction and optimization during design phase.

As an important indicator of the product, reliability has got more and more attention. However, it is still difficult to evaluate the reliability of industrial network system comprehensively during design phase. Over the years, scholars all over the world have carried out a lot of fruitful research results on the problem. A series of reliability analysis methods have been put forward such as reliability block diagram(RBD)[1], binary decision diagram[2], fault tree(FT)[3], bayesian networks(BN)[4] and petri net[5,6]. As a simple, direct and efficient method, RBD has been widely applied to engineering. For example, Dr. Dou proposed reliability evaluation model of ship to air missile launching system on the basis of RBD, achieved the reliability evaluation assessment when the single shot happened[7]. Dr. Chen established reliability modeling process based on ExtendSim on the basis of RBD to solve the modeling and programming difficulties of traditional reliability method[8]. Dr. Wu studied the reliability of spacecraft solar wing system following RBD and FT[9]. Dr. Sun introduced a layered hybrid model method to analyse the reliability of the airplane control system which is based on combining RBD and generalized stochastic Petri net[10].

Though RBD can effectively build reliability model and evaluate reliability of the system, it ignores the fact that the industrial network system is a typical hybrid system integrated with parts, electrical equipment, electronic components, control components and other units, whose impacts on system reliability are different. For example, it is obvious that a server failure has a greater influence than a circuit failure on system reliability. Therefore, considering the different influence of units on system reliability is more reasonable in the construction of reliability modeling. Thereby, engineers can conveniently recognize the weak link and optimize the system reliability during design phase.

Based on the above consideration, a multi-layer reliability evaluation system was established by AHP method for the industrial network system. Then, a multi-layer reliability evaluation model with weight coefficient of units was proposed. A case proved the effectiveness of the multi-layer reliability evaluation method which meets the needs of reliability evaluation in the development process of industrial network system.

2 Overview of industrial network system

Industrial network system is a full digital, bidirectional, multi-station communication system installed in the

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industrial production. It can be described that the system consists of a series of different hardware and software modules that play functions of data acquisition, data transmission, data processing and so on [11].

Industrial network system is a typical machine, electricity and control system. Any fault will result in production disruptions, even safety accidents, which will cause significant economic losses to the enterprise. As industrial 4.0 and made in China 2025 are put forward, quantities of industrial network system are rapidly increasing. Accordingly, reliability problems of industrial network system are constantly exposed and increasingly prominent. Due to the variety of parts, complex structure, high integration and so on, it is very difficult to accurately calculate the reliability of industrial network system by using the traditional reliability method. So, establishing a new reliability evaluation method that adapts to industrial network system is of great importance to improve reliability, reduce safety accidents and increase corporate profits.

3 The multi-layer reliability model

AHP is to decompose complex engineering problems from top to bottom to multiple levels and then solve the priority of each level to the upper level, so as to qualitatively and quantitatively analyze the problem or target. In this paper, system reliability model which reflects the importance of different units is constructed on the basis of AHP and RBD.

According to AHP method, industrial network system can be divided into four basic levels, namely system layer, subsystem layer, function module layer and basic module layer, as shown in figure 1. The upper layer is the target layer of next layer on reliability and the next layer is the basic unit of upper layer. The basic 4 layer can be increased or reduced in order to meet the analytic need for industrial network system with different complexity.

Every level reliability model is constructed based on RBD. For the series RBD, the reliability can be calculated as follows:

$$R_S(t) = \prod_i R_i^{w_i}(t) \tag{1}$$

where, R_s represents target reliability of the layer, t represents time, R_i represents unit i reliability of the layer, w_i represents the weight of unit i.

For parallel RBD, the reliability can be calculated as follows:

$$R_S(t) = 1 - \prod_i \left(1 - R_i^{w_i}(t)\right) \tag{2}$$

For next league or redundancy structure, reliability can be calculated by considering the impact of the weight coefficient. In theory, the weight coefficient w_i belongs to $[0, \infty)$ in the above formula.

When w_i equals to 0, R_i equals to 1 which shows that unit i has no effect on reliability for target layer. When w_i is close to ∞, R_i is close to 0 which means that unit i has a deterministic effect on reliability for target layer.

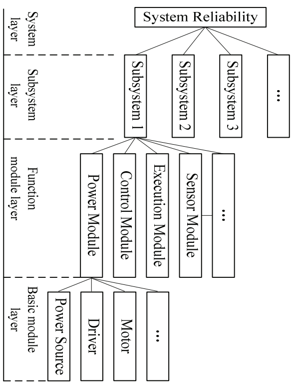

Figure 1. The multi-layer reliability evaluation system for industrial network system.

4 Weight coefficient calculating method

Weight is the most critical and difficult point when AHP method is used to analyze system reliability, that is to determine the weight coefficient in formula (1) and formula (2). AHP method needs to gain judgment matrix which can represent the relative importance of different index by experts[12]. Judgment matrix often adopts the proportional scaling method, and different proportion scales usually cause different results. Therefore, the fuzzy judgement matrix method is proposed in order to correctly evaluate system reliability by AHP in this paper. By the way, weight coefficients are able to truly reflect the relative importance of different index.

For the basic unit of each layer, index set needed to compare importance is as follows:

$$RPN = \left\{RPN_1, RPN_2, \dots, RPN_n\right\} \tag{3}$$

where, RPN_i is the risk priority number of unit i, $i = 1, 2, ..., n$, n is total unit number. This paper calculates RPN_i by combining the risk priority number method of Criticality Analysis (CA) with the failure model frequency rate[13]. The formula is as follows:

$$RPN_i = \sum_j \alpha_{ij} \cdot OPR_{ij} \cdot ESR_{ij} \tag{4}$$

where, *OPR* is probability level of the failure model of the unit; *ESR* is the effect severe degree of the unit to target layer. α is failure model frequency rate which means ratio of the failure mode in all failure for the unit; $j = 1, 2, \cdots$ is failure model frequency number for the unit. The grading criteria of *OPR* and *ESR* are presented in table 1 and table 2, respectively.

Table 1. The grading criterion of *OPR*.

***OPR* grading level**	**Probability level**	**Probability range**
1	the lowest	$P \le 10^{-6}$
2,3	lower	$10^{-6} < P \le 10^{-4}$
4,5,6	common	$10^{-4} < P \le 10^{-2}$
7,8	higher	$10^{-2} < P \le 10^{-1}$
9,10	the highest	$P > 10^{-1}$

Table 2. The grading criterion of *ESR*.

***ESR* grading level**	***ESR* level**
1,2,3	Mild (Do not lead to people injuries, mild product damage, property loss and environmental pollution, but plan disorder)
4,5,6	Medium (Lead to medium people injuries, product damage, task delay or demotion, medium property loss and environmental pollution)
7,8	Deadly (Lead to severe people injuries, product damage, task failure, severe property loss and environmental pollution)
9,10	Disastrous (Lead to the deaths of personnel, product damage, major property loss and disastrous environmental pollution)

According to the result calculated by formula (4), RPN_i and RPN_k in index set RPN takes binary comparison. If $RPN_i > RPN_k$, let $e_{ik} = 0, e_{ki} = 0$; If $RPN_i = RPN_k$, let $e_{ik} = 0, e_{ki} = 0$; If $RPN_i < RPN_k$, let $e_{ik} = 0, e_{ki} = 1$. The binary contrast matrix on index importance is as follows:

$$E = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1n} \\ e_{21} & e_{22} & \cdots & e_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ e_{n1} & e_{n2} & \cdots & e_{nn} \end{bmatrix} = \left(e_{ik}\right) \tag{5}$$

Further, f_i (the importance ranking index of RPN_i) can be calculated as follows:

$$f_i = \sum\nolimits_k e_{ik} \tag{6}$$

Ranking f_i by value, importance degree of reliability to upper layer is get accordingly for each unit. Thus, fuzzy judgement matrix W is able to be calculated indirectly which is similar to the binary contrast matrix, as follows:

$$W = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ w_{n1} & w_{n2} & \cdots & w_{nn} \end{bmatrix} = \left(w_{ik}\right) \tag{7}$$

where,

$$w_{ik} = \frac{f_i - f_k}{2(\mathrm{n}-1)} + 0.5 \qquad (i, k = 1, 2, \ldots, \mathrm{n}) \tag{8}$$

Through this transformation, the sort index of the index is used to transform the fuzzy indirect scale which can reflect the relative importance of each index. Construct a fuzzy judgment matrix (w_{ik}), we can get the fuzzy membership degree per line. According to the nature of the fuzzy judgement matrix W , fuzzy membership of each row is able to be calculated as follows:

$$w_i = \sum\nolimits_k w_{ik} \qquad (i \neq k) \tag{9}$$

where, w_i is the importance of index i to the upper layer, namely weight coefficient.

5 Case study

The reliability of the industrial network system for an electronic automatic assembly line was studied by the proposed multi-layer reliability evaluation method. The industrial network system of the electronic automatic assembly line is composed of data acquisition system, data transmission system and data processing system, as shown in figure 2.

5.1 Reliability analysis of module layer

In the case, reliability of each component is assumed to be exponential distribution and failure rate is λ . Each component parameters of failure rate, *OPR* and *ESR* are show in table 3. Failure model number of each component does not be considered to simplify the calculation. According to formula (4) and (5), the binary contrast matrix of each system in function module layer is calculated as follows:

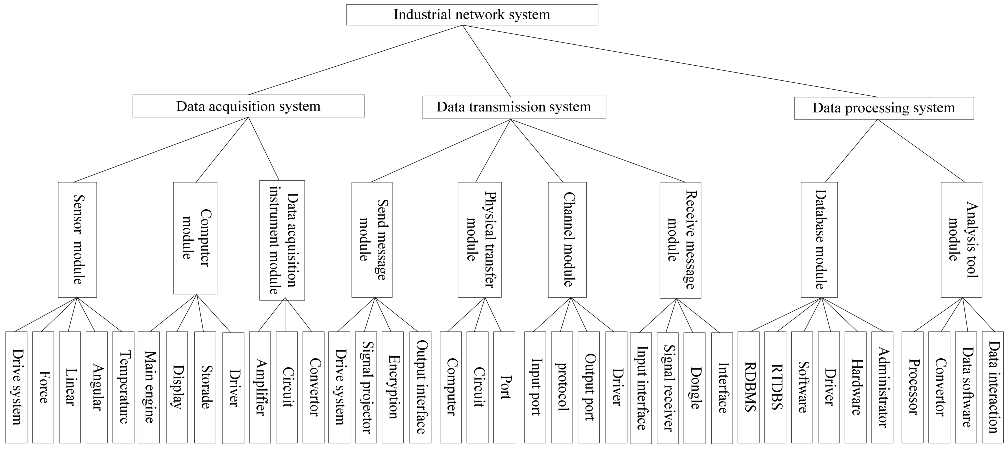

Figure 2. The multi-layer reliability evaluation system for the industrial network system of an electronic automatic assembly line.

Table 3. The failure rate, *OPR* and *ESR* of components.

Name of parts	λ **(10^{-6})**	***OPR***	***ESR***	**Name of parts**	λ **(10^{-6})**	***OPR***	***ESR***
Drive system	0.5	1	4	Output interface	1.5	2	1
Force	15	2	3	Computer	0.5	1	3
Linear	20	3	3	Port	2.5	1	4
Angular	1.5	1	3	Input port	15.5	3	1
Temperature	50.5	3	2	Protocol	18.5	2	4
Main engine	15.5	2	3	Output port	110.5	4	4
Display	130.5	4	1	Input interface	0.5	1	1
Storage	12.5	2	2	Signal receiver	0.5	1	1
Driver	1.5	2	1	Dongle	5.5	2	2
Amplifier	0.5	1	4	Interface	8.5	2	1
Circuit	3.5	2	3	RDBMS	5.5	2	4
Convertor	55.5	3	1	RTDBS	0.5	1	4
Signal projector	110.5	4	4	Software	23.5	3	3
Encryption	185.5	4	2	Hardware	14.5	3	1
Administrator	8.5	2	1	Processor	15.5	2	2
Data software	80.5	3	4	Data interaction	0.5	1	3

1) The binary contrast matrix of sensor module

$$E=\begin{bmatrix}0&0&0&1&0\\1&0&0&1&0\\1&1&0&1&1\\0&0&0&0&0\\1&0&0&1&0\end{bmatrix}$$

2) The binary contrast matrix of computer module

$$E=\begin{bmatrix}0&1&1&1\\0&0&0&1\\0&0&0&1\\0&0&0&0\end{bmatrix}$$

3) The binary contrast matrix of data acquisition instrument module

$$E=\begin{bmatrix}0&0&1\\1&0&1\\0&0&0\end{bmatrix}$$

4) The binary contrast matrix of send message module

$$E=\begin{bmatrix}0&0&0&1\\1&0&1&1\\1&0&0&1\\0&0&0&0\end{bmatrix}$$

5) The binary contrast matrix of physical transfer module

$$E=\begin{bmatrix}0&0&0\\1&0&1\\1&0&0\end{bmatrix}$$

6) The binary contrast matrix of channel module

$$E=\begin{bmatrix}0&0&0&1\\1&0&0&1\\1&1&0&1\\0&0&0&0\end{bmatrix}$$

7) The binary contrast matrix of receive message module

$$E=\begin{bmatrix}0&0&0&0\\0&0&0&0\\1&1&0&1\\1&1&0&0\end{bmatrix}$$

8) The binary contrast matrix of database module

$$E=\begin{bmatrix}0&1&0&1&1&1\\0&0&0&1&1&1\\1&1&0&1&1&1\\0&0&0&0&0&0\\0&0&0&1&0&1\\0&0&0&0&0&0\end{bmatrix}$$

9) The binary contrast matrix of analysis tool module

$$E=\begin{bmatrix}0&1&0&1\\0&0&0&0\\1&1&0&1\\0&0&0&0\end{bmatrix}$$

According to formula (6) ~ (8), fuzzy judgment matrix of each function module can be obtained in turn as follows:

1) Fuzzy judgment matrix of sensor module

$$W=\begin{bmatrix}0.5&3/8&1/8&5/8&3/8\\5/8&0.5&0.25&0.75&0.5\\7/8&0.75&0.5&1&0.75\\3/8&0.25&0&0.5&0.25\\5/8&0.5&0.25&0.75&0.5\end{bmatrix}$$

2) Fuzzy judgment matrix of computer module

$$W=\begin{bmatrix}0.5&5/6&5/6&1\\1/6&0.5&0.5&2/3\\1/6&0.5&0.5&2/3\\0&1/3&1/3&0.5\end{bmatrix}$$

3) Fuzzy judgment matrix of data acquisition instrument module

$$W=\begin{bmatrix}0.5&0.25&0.75\\0.75&0.5&1\\0.25&0&0.5\end{bmatrix}$$

4) Fuzzy judgment matrix of send message module

$$W=\begin{bmatrix}0.5&1/6&1/3&2/3\\5/6&0.5&2/3&1\\2/3&1/3&0.5&5/6\\1/3&0&1/6&0.5\end{bmatrix}$$

5) Fuzzy judgment matrix of physical transfer module

$$W=\begin{bmatrix}0.5&0&0.25\\1&0.5&0.75\\0.75&0.25&0.5\end{bmatrix}$$

6) Fuzzy judgment matrix of channel module

$$W=\begin{bmatrix}0.5 & 1/3 & 1/6 & 2/3\\ 2/3 & 0.5 & 1/3 & 5/6\\ 5/6 & 2/3 & 0.5 & 1\\ 1/3 & 1/6 & 0 & 0.5\end{bmatrix}$$

7) Fuzzy judgment matrix of receive message module

$$W=\begin{bmatrix}0.5 & 0.5 & 0 & 1/6\\ 0.5 & 0.5 & 0 & 1/6\\ 1 & 1 & 0.5 & 2/3\\ 5/6 & 5/6 & 1/3 & 0.5\end{bmatrix}$$

8) Fuzzy judgment matrix of database module

$$W=\begin{bmatrix}0.5 & 0.6 & 0.4 & 0.9 & 0.7 & 0.9\\ 0.4 & 0.5 & 0.3 & 0.8 & 0.6 & 0.8\\ 0.6 & 0.7 & 0.5 & 1 & 0.8 & 1\\ 0.1 & 0.2 & 0 & 0.5 & 0.3 & 0.5\\ 0.3 & 0.4 & 0.2 & 0.7 & 0.5 & 0.7\\ 0.1 & 0.2 & 0 & 0.5 & 0.3 & 0.5\end{bmatrix}$$

9) Fuzzy judgment matrix of analysis tool module

$$W=\begin{bmatrix}0.5 & 5/6 & 1/3 & 5/6\\ 1/6 & 0.5 & 0 & 0.5\\ 2/3 & 1 & 0.5 & 1\\ 1/6 & 0.5 & 0 & 0.5\end{bmatrix}$$

According to formula (9) and above fuzzy judgment matrix, the weight coefficient of each component is evaluated. Then, reliability of each module which is shown in table 4 is obtained on the basis of series RBD when system continuously works for 1000 hours. The failure rate of each module is shown in table 5.

Table 4. Reliability of each function module.

Module name	Reliability
Sensor module	0.811
Computer module	0.792
Data acquisition instrument module	0.979
Send message module	0.539
Physical transfer module	0.991
Channel module	0.803
Receive message module	0.969
Database module	0.851
Analysis tool module	0.754

5.2 Reliability analysis of subsystem

OPR and *ESR* of each function module are shown in table 5.

Table 5. Failure rate, *OPR* and *ESR* of each function module.

Module name	λ (10^{-4})	*OPR*	*ESR*
Sensor module	2.09	4	4
Computer module	2.33	5	3
Data acquisition instrument module	0.21	3	4
Send message module	6.18	5	3
Physical transfer module	0.09	3	4
Channel module	2.19	4	5
Receive message module	0.32	3	3
Database module	1.61	4	4
Analysis tool module	2.83	5	4

Similarly, according to formula (4) ~ (8), the fuzzy judgment matrix of each subsystem can be obtained in turn as follows:

1) Fuzzy judgment matrix of data acquisition system

$$W=\begin{bmatrix}0.5 & 0.75 & 1\\ 0.25 & 0.5 & 0.75\\ 0 & 0.25 & 0.5\end{bmatrix}$$

2) Fuzzy judgment matrix of data transmission system

$$W=\begin{bmatrix}0.5 & 2/3 & 1/3 & 5/6\\ 1/3 & 0.5 & 1/6 & 2/3\\ 2/3 & 5/6 & 0.5 & 1\\ 1/6 & 1/3 & 0 & 0.5\end{bmatrix}$$

3) Fuzzy judgment matrix of data processing system

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

According to formula (9) and above fuzzy judgment matrix, the weight coefficient of each function module is evaluated. Then, reliability of each subsystem which shows in table 6 is obtained on the basis of series RBD when system continuously works for 1000 hours. The failure rate of each subsystem is shown in table 7.

Table 6. Reliability of each subsystem.

Subsystem name	Reliability
Data acquisition system	0.5466
Data transmission system	0.1748
Data processing system	0.7535

5.3 Reliability analysis of system

OPR and *ESR* of each function module are shown in table 5.

Table 7. Failure rate, *OPR* and *ESR* of each subsystem.

Subsystem name	λ (10^{-3})	*OPR*	*ESR*
Data acquisition system	0.604	5	4
Data transmission system	1.744	5	5
Data processing system	0.283	4	3

Similarly, according to formula (4) ~ (8), the fuzzy judgment matrix of system can be obtained in turn as follows:

$$W=\begin{bmatrix}0.5 & 0.25 & 0.75\\ 0.75 & 0.5 & 1\\ 0.25 & 0 & 0.5\end{bmatrix}$$

According to formula (9) and above fuzzy judgment matrix, the weight coefficient of each subsystem is evaluated. Then reliability of system is 0.02407 on the basis of series RBD when system continuously works for 1000 hours. Failure rate and mean time before failure of the system are 0.003727 and 268 hours respectively.

The total failure rate and mean time before failure (MTBF) of the system are 0.0009785 and 1022 hours respectively by the traditional reliability method. Statistically, from 2013 to 2016, 36-time breakdowns happened in the cumulative working 11640 hours which means mean time before failure is actually 323 hours. It is obvious that the results evaluated by method in this paper are consistent with the actual situation.

6 Conclusion

Industrial network system that is integrated with machine, electricity and control system coexist various failure modes in the long running process. It is necessary to evaluate and predict industrial network system reliability during development process in order to guarantee reliability. Therefore, a multi-layer reliability method were introduced based on RBD and AHP in this paper. In the proposed method the different influences of units on system reliability are considered. It is convenient to recognize the weak link and optimize the system reliability during design phase for engineers by using the proposed method. Through the case analysis, it shows that the method is more reasonable than the traditional reliability analysis method, and the reliability prediction result is consistent with the engineering practice.

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