

Reliability Evaluation and Improvement Approach of Chemical Production Man - Machine - Environment System

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Abstract. In recent years, with the gradual extension of reliability research, the study of production system reliability has become the hot topic in various industries. Man-machine-environment system is a complex system composed of human factors, machinery equipment and environment. The reliability of individual factor must be analyzed in order to gradually transit to the research of three-factor reliability. Meanwhile, the dynamic relationship among man-machine-environment should be considered to establish an effective blurry evaluation mechanism to truly and effectively analyze the reliability of such systems. In this paper, based on the system engineering, fuzzy theory, reliability theory, human error, environmental impact and machinery equipment failure theory, the reliabilities of human factor, machinery equipment and environment of some chemical production system were studied by the method of fuzzy evaluation. At last, the reliability of man-machine-environment system was calculated to obtain the weighted result, which indicated that the reliability value of this chemical production system was 86.29. Through the given evaluation domain it can be seen that the reliability of man-machine-environment integrated system is in a good status, and the effective measures for further improvement were proposed according to the fuzzy calculation results.

1. Introduction

The production that raw materials are processed with a series of chemical or physical methods to give one or more products with different uses and physical and chemical properties [1] is regarded as chemical production, in which the input and output of materials occur. In the production process, the important features are as follows: (1) There is a fixed production process, at the same time, the production procedure is uninterrupted; (2) The input material is generally gas, liquid or solid particles; (3) The production flow is established, in which special equipment will be used; (4) There is little human operation, instead, automated processes are applied.

The man-machine-environment system in the chemical production needs to go through scientific research and systematic approach to determine the relationship among the three elements [3], and form an effective mechanism for studying the entire man - machine - environment system [4]. Human, as the subject of the system, refers to not only the individual, but also the group of people; Machine means all the machinery equipment which need to be controlled and mastered in the operation



procedure, including machine parts, related devices, and conveyances and so on; Environment is where human and machines complete the work together, including not only the internal environment, but also the natural environment, the social environment and the artificial environment. This system shows more complexity, which is mainly to regard these three as one subject, and form a safe and complex powerful system through the processing and delivery of information. Meanwhile, its security and economic value are reflected through the contents of the system engineering, in order to minimize or get rid of the accidents harmful to human body, and minimize the investment and increase the output when fulfilling the requirements of the system to guarantee the increase of economic benefits. The main purpose of the establishment and application of this system is to effectively combine the three aspects considering the practicality characteristics of soft science, in order to solve the realistic problems in production, and guarantee the safety of personnel, equipment and environment.

2. Theoretical analysis of reliability of man - machine - environment system

2.1. Theoretical analysis of human error

According to the study, the proportion of human errors in the equipment failure is 20% to 50%, with various forms, which mainly because people need to do different things in different ways. There are three major forms: The first is lazy error, such as instrument parallax, and the slip of the pen when taking notes and so on. These are mostly due to psychological or physical errors. The second is called environmental error defined as the changes of emotion and consciousness caused by the environmental change, which means the operational error due to the fatigue and discomfort caused by the change of working environment [5]. Finally, it is the error formed in the human-computer interaction, which is because of the unsuitable state caused by the difference of the display or controller of man-machine interface during design.

2.2. Theoretical analysis of environmental impact

(1) Temperature. According to the survey, the impact of temperature on the staff is intuitive. At 25 °C, human body feels comfortable, while above or below this temperature significant changes will be obvious. When it is above 25 °C, people begin to sweat to slow down the body temperature rise, and when the temperature reaches 32 °C, the error rate of workers will be significantly increased; However, when the temperature is below 25 °C, especially below 10 °C human body constricts the blood vessels against excessive energy loss.

(2) Noise environment. It has a certain impact on the psychological state of the chemical production personnel, and interferes with their regular work. During the long-term operation in the noise environment, the probability of human errors will be greatly enhanced, and the work efficiency will be reduced.

(3) Air environment. The effect of air environment on the chemical production personnel is relatively great. It is easy to impair the health of workers, and may affect the normal operation of chemical production network, resulting in significant loss of enterprise property. The most important and widespread impact is that the air pollution from the production will cause harm to the life and health of the surrounding people due to air mobility, and the surrounding people's lives and the body will, the influence range is relatively wide and hard to be controlled.

2.3. Theoretical analysis of machinery equipment failure

Machinery equipment failure can be regarded as the situation in which the entire system occurs failure or cannot run, since the machine and equipment lose part or all the functions in the working process. The number of machines and equipment used in production is large, hence, there will be varying degrees of problems with the machinery equipment failure affected by many aspects [6], for instance, the operator makes fault in the course of operation, the machine encounters problem due to the long-time use or other factors, and the using environment changes. All of these will have a direct or indirect impact on the machines and equipment to form a certain failure.

Equipment failure in the production can be divided into three stages, which mainly refers to the changing procedure of a machine after put into use, with the increase of the utility time and the failure occurring in the process of equipment from opening to retire. The early failure refers to the run-in process owing to the personnel and equipment when the equipment starts to be used for production. On the one hand the equipment remains problem in the design and manufacture procedures, and on the other hand the personnel is lack of skills. However, the problems will gradually decrease with the increase of the utility time, and after a period of run-in process it will reach the best state, with the gradual reduce of failure rate. Occasional failure means the sudden failure in operation, and the main reasons for this failure are a series of accidental factors, such as the operation errors, insufficient maintenance, hidden danger of some materials, and defects of manufacturing process. There is no specific mechanism for the existence of occasional failure which occurs randomly. The third stage is that the fit quality and overall rate of the parts reduce after the long-term use of the machine, because of wear or increase of working strength, and the damage is mainly due to the machine aging.

3. Reliability Evaluation of Man- Machine - Environment System in Chemical Production

3.1. Reliability evaluation procedure of man- machine - environment system

3.1.1. *Select and construct the index system.* First, the evaluated indexes should be selected according to certain principle and method, and the corresponding hierarchy should be built, generally divided from small to large into the index layer (C), the criterion layer (B) and the target layer (A). In the integrated system of man- machine - environment in chemical production, the reliability evaluation needs to be considered various factors and the importance of each factor, due to the comprehensiveness of the system. Therefore, in the selection of influence factors, the factors with great significance to the subject evaluation must be selected, in order to find more specific factor index from the uncertainty.

3.1.2. *Calculation of index weight.* (1) Establish the index set. When expressing the above selected indexes, they can be divided into the main and sub factor sets, of which the main factor set is a set of criterion layer factors, expressed as $A = (B_1, \dots, B_i)$, while the sub factor set refers to the set of index layer factors, expressed as $B_i = (C_1, \dots, C_i)$. (2) Set the evaluation domain. $V = (\text{Excellent, good, average, fair, poor})$. (3) Calculate the index weight. The calculation of index importance of each layer should be done following the judgment basis originated from judgment matrix scale, with the meaning shown in Table 1.

Table 1. Judgment matrix scale and its meaning.

Scale	Meaning
1	The former and latter are equally important
3	The former is slightly more important than the latter
5	The former is obviously more important than the latter
7	The former is significantly more important than the latter
9	The former is extremely more important than the latter
2,4,6,8	Take the median of two adjacent judgments

According to the above scale meaning, the main factors (W) are sorted and calculated the weight by the eigenvalue method. That is $W = (W_1, \dots, W_i)$, thus $W_i = \frac{V_i}{\sum_{i=1}^n V_i}$, while $V_i = \sqrt[n]{\prod_{j=1}^n a_{ij}}$ ($i=1,2,3,\dots,n$). The formula can be used to obtain the corresponding value and calculate the weight, and during the calculation the consistency of weight need to be calculated and verified to enhance the reliability and

satisfaction of the results, the weight, and during the calculation the consistency of weight need to be calculated and verified to enhance the reliability and satisfaction of the results.

3.1.3. Evaluate *the fuzzy results*. (1) Determine the membership matrix U. The fuzzy relation is established with the corresponding domain (Vi) of each sub factor set (Bi), and the membership matrix is constructed.

$$U_i = \begin{bmatrix} u_{11} & u_{12} & u_{13} & \cdots & u_{1m} \\ u_{21} & u_{22} & u_{23} & \cdots & u_{2m} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ u_{n1} & u_{n2} & u_{n3} & \cdots & u_{nm} \end{bmatrix} \quad (1)$$

(2) Calculate the criterion layer Bi.

$$B_i = W_i * U_i (i=1, \dots, i) \quad (2)$$

(3) Establish the total fuzzy evaluation matrix U

$$U = \begin{bmatrix} B_1 \\ B_2 \\ \vdots \\ B_i \end{bmatrix} \quad (3)$$

(4) Form the evaluation results

$$A = U * W \quad (4)$$

The reliability evaluation of the corresponding system is conducted through the calculated fuzzy result.

3.2. Progressive reliability evaluation of man - machine - environment system

3.2.1. *Reliability evaluation of human factors in chemical production system*. (1) Selection and construction of evaluation index. In the chemical production process, there are many factors influencing personnel, which are mainly from the environment, organization, technology and personal factors, as shown in Table 2.

(2) Establish the index factor set. The above selected indexes are expressed in the form of factor sets, as $A = (B_{11}, B_{12}, B_{13}, B_{14})$; $B_{11} = (C_1)$; $B_{12} = (C_2, C_3, C_4)$; $B_{13} = (C_5, C_6)$; $B_{14} = (C_7, C_8, C_9, C_{10})$.

(3) Calculation of evaluation index weight

In order to obtain personnel reliability data, five relevant experts evaluate the reliability of chemical production staff on the field, and score according to the evaluation domain $V = (\text{Excellent, good, average, fair, poor})$, which is generally $V = (100 \text{ points, } 80 \text{ points, } 60 \text{ points, } 40 \text{ points, } 20 \text{ points})$. Ultimately the evaluation will be expressed in accordance with the score to obtain the main factor judgment matrix (Table 3) so that the weight can be calculated.

Table 2. Selection of reliability evaluation index of human factors.

Target layer A	Criterion layer B ₁	Index layer C
Reliability evaluation of personnel A	Environmental factor B ₁₁	Production environment C ₁
	Organizational factors B ₁₂	Production management C ₂
		Production load C ₃
		Production training C ₄
	Technical factors B ₁₃	Operation ability C ₅
		Skill level C ₆
	Personal factors B ₁₄	Education C ₇
		Seniority C ₈
		Psychological quality C ₉
		Physical quality C ₁₀

Table 3. Human factor judgment matrix.

	Environmental factor	Organizational factor	Technical factor	Personal factor
Environmental factor	1	1/2	1/3	1/5
Organizational factors	2	1	1	1/3
Technical factor	3	1	1	1/2
Personal factor	5	3	2	1

The weight vector W is obtained by the judgment matrix, and for easy distinction, the weight vector of the human factor is set to W₁, thus W₁ = (0.4899, 0.2312, 0.1896, 0.0895).

The remark set of basic data distribution can be generated from the score of the experts' evaluation of each index. See Table 4 for details.

Table 4. Remark set of basic data distribution.

	Excellent	Good	Average	Fair	Poor
Environmental factor	0.65	0.25	0.10	0.00	0.00
Organizational factors	0.55	0.35	0.10	0.00	0.00
Technical factor	0.65	0.25	0.10	0.00	0.00
Personal factor	0.75	0.15	0.10	0.00	0.00

The fuzzy relation matrix U₁ can be generated from the above values, and finally obtained from the formula that:

$$B_1 = W_1 \times U_1 = (0.6800, 0.2198, 0.1001, 0.0000, 0.0000)$$

3.2.2. Reliability evaluation of machinery equipment in chemical production system. (1) Selection and construction of evaluation index. In the reliability evaluation of the equipment, the impact analysis cannot be carried out from the single small mechanical unit, but to treat the machine as a whole and consider many other factors, in order to more accurately analyze the factors leading to the most serious impact when equipment failure occurs. Similarly, in chemical production system, there are also many factors affecting the machinery equipment, mainly from environmental factors, human factors and material factors. See Table 5.

Table 5. Selection of reliability evaluation index of machinery equipment.

Target layer A	Criterion layer B ₂	Index layer C
Reliability evaluation of machinery equipment A	Environmental factor B ₂₁	Equipment working environment C ₁
	Human factors B ₂₂	Operational skills C ₂
		Operational experience C ₃
		Maintenance C ₄
	Material factors B ₂₃	Training C ₅
		Quality of raw material C ₆
		Maintenance of raw material C ₇

(2) Establish the index factor set.

The above selected indexes are expressed in the form of factor sets, as

A= (B₂₁, B₂₂, B₂₃). B₂₁= (C₁); B₂₂=(C₂, C₃, C₄, C₅); B₂₃=(C₆, C₇).

(3) Calculation of evaluation index weight

The main factor judgment matrix is generated by pair comparison of the data obtained from the experts' score (Table 6).

Table 6. Human factor judgment matrix.

	Environmental factor	Human factor	Material factor
Environmental factor	1	1/6	1/3
Human factor	6	1	4
Material factor	3	1/4	1

The weight vector W₂ is obtained by the judgment matrix, thus W₂= (0.6911, 0.2175, 0.0910).

The remark set of basic data distribution can be generated from the score of the experts' evaluation of each index. See Table 7 for details.

Table 7. Remark set of basic data distribution.

	Excellent	Good	Average	Fair	Poor
Environmental factor	0.25	0.35	0.25	0.15	0.00
Human factor	0.55	0.20	0.20	0.05	0.00
Material factor	0.15	0.35	0.30	0.20	0.00

The fuzzy relation matrix U₂ can be generated from the above values, and finally obtained from the formula that:

$$B_2=W_2 \times U_2=(0.4356, 0.2261, 0.2466, 0.0917, 0.0000)$$

3.2.3. Reliability evaluation of environment in chemical production system. (1) Selection and construction of evaluation index. The working environment is a scope of man-machine-environment system. As a spatial scope, whether it can make people feel comfortable in the work space is also a reason for the human error. A good working environment provides a relaxed and comfortable space, so that the workers are more efficient at work, so as to avoid the errors resulted by the impact of spatial environment, thereby enhancing the reliability of the system. In the working environment, the environmental factors influencing people include mainly noise pollution, air pollution and climate factors, as shown in Table 8.

Table 8. Selection of reliability evaluation index of machinery environment.

Target layer A	Criterion layer B ₃	Index layer C
Reliability evaluation of environment A	Noise pollution factor B ₃₁	Noise C ₁
	Air pollution factors B ₃₂	Hazard gas C ₂
		Dust C ₃
	Climatic factors B ₃₃	Temperature C ₄
Humidity C ₅		

(2) Establish the index factor set.

The above selected indexes are expressed in the form of factor sets, as

$A = (B_{31}, B_{32}, B_{33}); B_{31} = (C_1); B_{32} = (C_2, C_3); B_{33} = (C_4, C_5).$

(3) Calculation of evaluation index weight

The main factor judgment matrix is generated by pair comparison of the data obtained from the experts' score (Table 9).

Table 9. Human factor judgment matrix.

	Noise pollution factor	Air pollution factor	Climatic factor
Noise pollution factor	1	6	3
Air pollution factor	1/6	1	1/3
Climatic factor	1/3	3	1

The weight vector W_3 is obtained by the judgment matrix, thus $W_3 = (0.6544, 0.2498, 0.0957).$

The remark set of basic data distribution can be generated from the score of the experts' evaluation of each index. See Table 10 for details.

Table 10. Remark set of basic data distribution.

	Excellent	Good	Average	Fair	Poor
Noise pollution factor	0.45	0.25	0.20	0.10	0.00
Air pollution factor	0.35	0.25	0.25	0.15	0.00
Climatic factor	0.15	0.25	0.30	0.30	0.00

The fuzzy relation matrix U_3 can be generated from the above values, and finally obtained from the formula that:

$$B_3 = W_3 \times U_3 = (0.3654, 0.2501, 0.2299, 0.1546, 0.0000)$$

3.2.4. Reliability comprehensive evaluation of man - machine - environment system in chemical production. (1) Selection and construction of evaluation index. The evaluation index of the single factor of man-machine-environment was selected through the analysis of each man-machine-environment subsystem in chemical production, which simplifies the selection of evaluation index of three factors of man-machine-environment, so that the comprehensive fuzzy evaluation of the system can be finally carried out. First, establish evaluation index target layer U with setting personnel as U_1 , machinery equipment as U_2 , environment as U_3 , thus $U = (U_1, U_2, U_3)$, then the established index system is as shown in table 11.

Table 11. Selection of reliability evaluation index of man-machine-environment.

Target layer	Criterion layer	Index layer
Reliability comprehensive evaluation of man-machine-environment U	Human factors U ₁	Environmental factor U ₁₁
		Organizational factors U ₁₂
		Technical factor U ₁₃
		Personal factor U ₁₄
	Machinery equipment U ₂	Environmental factor U ₂₁
		Material factor U ₂₂
		Human factor U ₂₃
		Climatic factor U ₃₁
	Environment U ₃	Noise pollution factor U ₃₂
		Air pollution factor U ₃₃

(2) Establish the index factor aggregate.

The above selected indexes are expressed in the form of factor sets, thus the sub factor sets are:

$$U_1=(U_{11}, U_{12}, U_{13}, U_{14}); U_2=(U_{21}, U_{22}, U_{23}); U_3=(U_{31}, U_{32}, U_{33})$$

(3) Calculation of evaluation index weight.

The main factor judgment matrix is generated by pair comparison of the data obtained from the experts' score (Table 12).

Table 12. Human factor judgment matrix.

	Environmental factor	Human factor	Machinery equipment factor
Environmental factor	1	1/2	2
Human factor	7	1	1/3
Machinery equipment factor	3	1/7	1

The weight vector W₂ is obtained by the judgment matrix, thus W=(0.6155,0.2924,0.0927).

The index vectors B₁, B₂ and B₃ obtained from the fuzzy evaluation of the three single factors of human, machine and environment are substituted into the fuzzy relation matrix to give the reliability comprehensive evaluation result of the man-machine-environment system in production. Calculated as follow:

$$B=(0.6155,0.2924,0.0927) \times \begin{bmatrix} 0.6801 & 0.2198 & 0.1001 & 0.0000 & 0.0000 \\ 0.4356 & 0.2261 & 0.2466 & 0.0917 & 0.0000 \\ 0.3654 & 0.2501 & 0.2299 & 0.1546 & 0.0000 \end{bmatrix}$$

$$=(0.5801,0.2209,0.1503,0.0397,0.0000)$$

The reliability fuzzy evaluation result has been obtained, and can receive the proportion determine. Since the evaluation domain has been set and given a certain assignment in the beginning, the interval can be set in accordance with the assignment V = (100 points, 80 minutes, 60 minutes, 40 minutes, 20 points), and the result is shown in Table 13.

Table 13. Interval setting for evaluation domain.

Scoring interval	Result description
90-100	Excellent
80-90	Good
70-80	Average
60-70	Fair
Below 60	Poor

According to the above $B=(0.5801, 0.2209, 0.1503, 0.0397, 0.0000)$, its proportion can be regarded as $V=(58.01\%, 22.09\%, 15.03\%, 3.97\%, 0.00\%)$, and with the above setting of weighted values, the result can be generated as follows:

$$58.01\% \times 100 + 22.09\% \times 80 + 15.03\% \times 60 + 3.97\% \times 40 + 0.00\% \times 20 = 86.29$$

The calculation shows that when the values in vector form are quantified to be between 0 and 100, the result becomes clearer. If the reliability of the complex and uncertain man - machine - environment system can be quantified to a number or result, it will be easier to grasp the reliability of such systems. The weighted result indicates that the reliability value of the chemical production system is 86.29, and through the evaluation domain, it can be seen that the reliability of man - machine - environment integrated system is at a good level.

3.3. Improvement measures for reliability of man-machine-environment system in chemical production

The three subsystems consisting of man-machine-environment form the chemical production network together, but the relationships of man-machine, man-environment, and machine-environment are of vital importance. Whether there are reasonable coordination and coordinated planning will determine the overall reliability of the system.

(1) Improvement measures for the reliability of work environment

The environmental impact of noise on the surrounding system is determined according to the actual situation. According to the comprehensive measures, the noise evaluation method can reduce the influence of noise on unreliable environmental factors. The concrete steps can include: Let workers wear high quality earphones, and adopt the work rotation system, with these two methods to reduce the interference of noise in the working procedure as much as possible. As for the harm of hazard gases, the measures of enhanced ventilation, application of appropriate positive measures and reduction of the concentration of hazard gases can be used. Ensure the workers to adapt to the environment without any damage of health, in order to achieve the effective combination of human, machine and environment to realize the further development of systems engineering.

(2) Improvement measures for the reliability of machinery equipment system

The reliability of machine and equipment is mainly affected by the investment funds, and the purchase of more advanced or upgrading products, which usually enhance the reliability of machinery equipment. However, the improvement by these methods is a financial burden for the enterprise, and higher technical equipment has more requirements for the staff. Therefore, it is necessary in the process, to take into account the relationship among human, financial and material, and measure uniformly the system update [7]. Based on the fact, the weakest link in the entire system can be improved to maintain the reliability of the system and enhance the overall capacity of the system. When selecting process system and machinery equipment, it is necessary to consider not only the management of funds, but also the comprehensive evaluation and consideration of man-machine-environment, to analyze the factors and conditions in the implementation process, and improve the overall level by increased management.

(3) Improvement measures for the reliability of-human factor

Human is the dominant factor in the process of chemical production, and how to control the individual in the network plays a key role for the chemical production network. To establish more

strict management measures for technical staff, and to improve the physical and psychological quality of technical staff, it requires the chemical producers to have proper physical condition to meet the work requirements, positive attitude, high security awareness, and high sense of crisis prevention. Moreover, strengthening the training of employees can help them to better adapt to complex and changeable work to reduce human error.

Control of human factors needs to improve not only the quality of personnel, but also the quality of technology. In the chemical production process, if works are not familiar with the machinery equipment and the operation, the different parts and procedure of operation process will caused great damage to the compatibility of personnel and equipment in chemical production process, and increase the probability of error. Therefore, in the design of machinery equipment, it needs to meet the characteristics and needs of human, so that the machine is more in line with the human features. For the place prone to errors, appropriate warning is in need to improve the cognition of staff for their positions, and establish the security defense system.

In the production process of chemical projects, the environment will directly affect the efficiency of workers. Hence, the control of human error can start from the control of the environment, and the establishment of a comfortable operating environment is particularly significant for employees [8]. Analysis shows that the environments affecting staff are as followings; the working environment, social environment, behavioral environment and family environment. From the analysis of these aspects, it can be seen that the work environment needs to be more safe and comfortable to promote the concept of safe production, and take safety as the focus of the enterprise to ensure a safe production atmosphere, and implant it into the awareness of employees. The good social atmosphere and social environment, the respect for staff and the understanding in the chemical production process are the guarantee for the good job of staff. Employees in the chemical production have to be responsible for their own behavior. A harmonious and good behavior environment plays a key role for the staff to establish a good working attitude and to throw themselves into the work, in order to reduce human errors. When leaders pay more care and attention to the families of employees, they will relax at work and play the greatest initiative.

4. Conclusion

With the extension of reliability research, the researches on the reliabilities of various systems have become the research emphases in various fields or industries. The research on the production system reliability is often the hot content of scholars, for instance, CNC machine tools, chemical systems, processing systems, and mineral system. Man-machine-environment system is a complex system, and the research is required to comprehensively analyze the reliability of human factors, environment, and machine, in order to effectively establish a comprehensive fuzzy evaluation. Currently, the study about the complex system like man-machine-environment is not common, hence, in this paper the man-machine-environment system in chemical production was studied, aiming to establish more effective fuzzy evaluation method for the reliability evaluation of this type of complex system. In this paper, the study was on the basis of the basic theories such as reliability theory, fuzzy theory and system engineering theory, and gradually analyzed the human errors which affect the reliability of human factors, the interference factors influencing the environment system, and the failure factors affecting the normal operation of machinery equipment. Through the analysis, the index factors affecting the man-machine-environment were specified, and then the reliability vector of the secondary target layer was analyzed step by step through the fuzzy evaluation, so that the reliability evaluation of man-machine-environment integrated system was finally carried out. The evaluation result was set and quantized with weighted value, and the reliability result after quantization was 86.29, which was at a good level according to the evaluation domain set by the weighted value and it also indicated that the selected man-machine-environment system was in a good state. Hence, in this paper, the effective way for further improvement was proposed based on this weighted results.

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