PAPER • OPEN ACCESS

# Research on Product Safety Assessment Method Based on Spacecraft Assembly Process

To cite this article: Zhibin Liu *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **569** 032044

IOP Conf. Series: Materials Science and Engineering **569** (2019) 032044 doi:10.1088/1757-899X/569/3/032044

# Research on Product Safety Assessment Method Based on Spacecraft Assembly Process

**Zhibin Liu[1,2*], Zhiming Li[1], Yi Lu[1,2], Yu Wang[1,2]**

[1]Beijing Institute of Spacecraft Environment Engineering, Beijing 100094, China

[2]Beijing Engineering Research Center of the Intelligent Assembly Technology and Equipment for Aerospace Product, Beijing 100094, china

*Corresponding author's e-mail: raindown@126.com Tel: 13466503260

**Abstract.** Based on the analysis and identification of risk factors in spacecraft assembly process, the safety evaluation model of spacecraft assembly process is constructed. Form a multi-dimensional safety evaluation parameter system. After investigating the safety evaluation methods in related fields, the method of combining the analytic hierarchy process (AHP) with the fuzzy evaluation method is determined to carry out the evaluation work, and the comprehensive safety evaluation results are obtained. The result of the evaluation is accurate and objective, which lays a solid foundation for the safety evaluation of spacecraft assembly process products.

## 1. Introduction

Spacecraft assembly is the process of assembling, connecting, testing and integrating instruments, components, cables and pipelines delivered by each subsystem to form final products, which is an important link in the process of spacecraft development. Spacecraft has the characteristics of complex structure, many sensitive components, many flexible components and many moving parts. The quality and safety problems occur in the assembly stage, such as bumping, scratching, crushing and lighting caused by the inadequate safety protection of the assembly, will cause damage or even scrap of key instruments and components, often bring losses to the development process of spacecraft, and some affect the whole process. The progress and cost of the development process have resulted in serious consequences.[1][2][3]

Therefore, the research on product safety evaluation method based on spacecraft assembly process can effectively avoid or reduce all kinds of damage that may occur in spacecraft assembly process, and improve the safety risk control capability of spacecraft products.[4]

In order to ensure the correctness of the model and the accuracy of the evaluation method, the specific work includes:

(1) Investigate the comprehensive application of safety at home and abroad, understand the latest technology trends and research progress at home and abroad.

(2) Combining with the analysis and identification of risk factors in spacecraft assembly process, the safety risk of spacecraft assembly process is measured, and the model is constructed with the selected method.

(3) Combining with the model, the safety evaluation work is carried out and the model case verification is carried out.

## 2. Research on Safety Assessment Technology and Modelling Method

### *2.1. Research on Safety Assessment Technology*

By investigating the related literatures of safety comprehensive analysis and design, process, process modelling and analysis of complex systems and processes at home and abroad, and collating and absorbing the engineering manuals, specifications and standards related to the assembly process of NASA, ESA and other foreign spacecrafts, the research results are shown in Table 1.

Table 1. Overseas Situation of Spacecraft Safety Research.

| Serial number | Company | Research and Practice Activities |
|---|---|---|
| 1 | ESA European Space Agency | A large number of standards have been developed for the management of space products and applications:<br>ECSS-Q-20b《Space Product Assurance-Quality Assurance》<br>ECSS-Q-20-09《Space Product Guarantee-Non-Uniform Control System》<br>ECSS-Q-30《Space Product Guarantee-Dependency》 |
| 2 | SATO, American Organization for Spacecraft Assembly and Testing | SATO provided full support for the Apollo Project (LM). Operational Checkout Procedures (OCPs) is one of their new methods. |
| 3 | DFL, David Florida Laboratory, Canadian Space Agency | DFL is responsible for assembling and testing all parts of the aircraft before take off, and testing various models to confirm that the function of the aircraft meets the requirements. |
| 4 | Alenia Spazio, Italy | Alenia Spazio, which is responsible for satellite assembly, integration and testing, has put forward its own new design method, assembly process and testing technology. |

From the above table, it can be seen that the establishment of safety assessment model for assembly is a key method to improve the safety of assembly

### *2.2. Investigation on Safety Risk Assessment Method*

After the establishment of the parameter system, in order to obtain the comprehensive risk assessment results, the index synthesis method should be determined according to the engineering properties and characteristics of the parameters in the parameter system, and the results with quantitative indicators can be obtained.

There are many kinds of techniques and methods for system security risk assessment. Through investigation, potential schemes and comparison of various modelling methods, the results are shown in Table 2.

Table 2. Comparison results of various modelling methods.

| Serial number | Method name | Whether quantitative | Advantage | shortcoming |
|---|---|---|---|---|
| 1 | Fault Tree Analysis (FTA) | yes | This graphical method is clear and easy to understand, so that people can see the logical relationship between the events described at a | There are many steps, and the calculation is more complicated. There is less data in China, and a lot of work needs to be done to carry out |

| | | | | |
|---|---|---|---|---|
| | | | glance. | quantitative analysis. |
| 2 | Process Failure Mode and Consequence Analysis (PFMEA) | yes | | High requirements for analysts |
| 3 | Hazard and operability analysis (HAZOP) | no | Identify subtle potential threats and improve the quality of employees' operations | The use of manpower, material resources and time-consuming; relying on expert experience |
| 4 | Expert Opinion Law (Delphi Law) | yes | Simple and easy to do | Not all projects are qualified for the high level of experts required to participate in the evaluation. |
| 5 | Analytic Hierarchy Process (AHP) | yes | Combining deduction and induction to solve complex problems, both qualitative analysis and quantitative results can be obtained. | It is often required to weigh and balance the practicability and operability of decision analysis models. |
| 6 | Comprehensive Risk Analysis | no | | This method requires a lot of data support and a lot of work. |
| 7 | Fuzzy Judgment Method | no | Mathematical model is simple and easy to master. | |

For spacecraft assembly process, the evaluation method should meet the following requirements:

(1) Expert experience data can be present in the model and the evaluation results are authoritative;

(2) It can reflect the evaluation results more objectively and reduce the errors caused by the differences of experience among different personnel.

(3) It can not only qualitatively give the evaluation results, but also quantify the risk value.

After comparative analysis, the combination of analytic hierarchy process (quantitative method) and fuzzy evaluation method (non-quantitative method) was selected to carry out safety evaluation.

## 3. Construction of Safety Evaluation Model

### *3.1. Objectives of Model Building*

The objective of building a safety evaluation model for spacecraft assembly process is:

(1) The safety risk of spacecraft assembly process is measured semi-quantitatively, and the comprehensive evaluation results of safety risk level are given.

(2) Identify the weak links in the assembly process through the results of risk assessment.

### *3.2. Safety evaluation parameter system*

Considering various factors that may affect the process of spacecraft assembly, such as personnel, objects, equipment, environment, methods, etc., starting from meeting the requirements of risk assessment that can be implemented and operated, according to the qualitative analysis results of risk factors and combining with the actual engineering situation, a safety evaluation parameter system is established as shown in Figure 1, which provides the necessity for further semi-quantitative risk assessment. Basic and prerequisite conditions.[5]

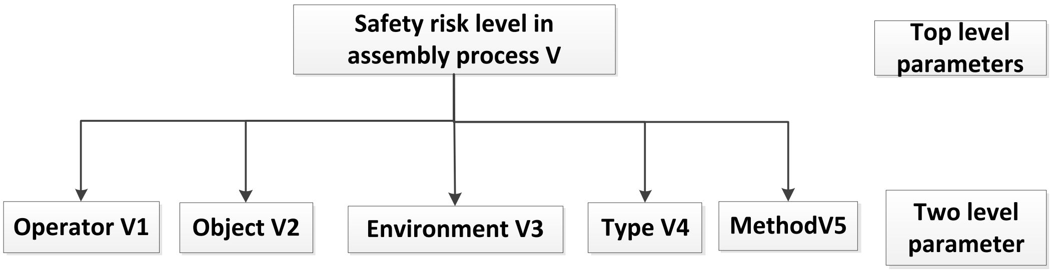


Figure 1. Safety Evaluation Parameter System of Spacecraft Assembly Process.

## 4. Application of Safety Assessment Method

### *4.1. Analytic Hierarchy Process*

The basic idea of Analytic Hierarchy Process (AHP) is to determine the relative importance of the parameters in the hierarchy according to the hierarchical structure of the established evaluation parameter system. Then, the relative weights of each parameter at each level to a certain parameter at the upper level are obtained by using the method of extracting the eigenvector of the judgment matrix, so as to support the comprehensive evaluation of safety risk by using the method of fuzzy comprehensive evaluation. The evaluation steps are as follows:[6][7]

By comparison in pairs, the judgment matrix is constructed: it is assumed that the sub-parameters of the next layer of parameter A are u1, u2, …, un, the proportion scale of the importance of parameter ui and uj relative to parameter A is represented by aij, and its value is assigned on the scale of "1~9". The meaning of scale 1~9 is shown in Table 3.

Table 3. Scale meaning.

| Scale | Meaning |
|---|---|
| 9 | The former is more important than the latter in expressing the comparison between the two parameters. |
| 7 | The former is more important than the latter in expressing the comparison between the two parameters. |
| 5 | It shows that the former is more important than the latter in comparing the two parameters. |
| 3 | The former is slightly more important than the latter. |
| 1 | Represents the same importance as two parameters |
| 2, 4,6,8 | Represents the median value of the above adjacent judgements |
| Reciprocal | If the importance ratio of factor *ui* to *uj* is *aij*, then the importance ratio of parameter *uj* to *ui* is *aij*=1/*aij* |

For target A, a two-to-two comparison judgment matrix is obtained by comparing the relative importance of n elements. $A=(a_{ij})_{n\times n}$ can be remembered as

$$A=\begin{vmatrix} 1 & a_{12} & \cdots & a_{1n} \\ a_{21} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{vmatrix}.$$

### *4.2. Fuzzy Judgment Method*

Because the safety state of spacecraft assembly process and the expression of safety evaluation results reflect a certain degree of fuzziness, that is, the boundary of safety level is not clear, the fuzzy evaluation method is used to achieve the synthesis of safety comprehensive evaluation indicators. The basic steps of the evaluation are as follows:

(1) Determining the level of factors

Let the factor rank of evaluation be $U = \{u_1, u_2, \ldots, u_i, \ldots, u_m\}$, i=1, 2,…, m. ui is the first factor in the first level, which is determined by n factors in the second level, $U_i = \{u_{i1}, u_{i2}, \ldots, u_{ij}, \ldots, u_{in}\}$, j=1, 2,…, n.

(2) Establishing Weight Set

According to the importance of each factor in each level, each factor is given corresponding weight. The set of weights is as follows:

First level $A = \{a_1, a_2, \ldots, a_i, \ldots a_m\}$, *i=1, 2,…, m*;

Second level $A_i = \{a_{i1}, a_{i2}, \ldots, a_{ij}, \ldots, a_{in}\}$, *j=1, 2,…, n*.

(3) Determining alternative set V

The alternative set is a set of all kinds of general judgement results that the judges may make to the judges. Regardless of the level of judgement, there is only one alternative set. The alternative set can be expressed as $V = \{v_1, v_2, \ldots, v_p\}$, *p=1, 2,…*.

From a technical point of view, the number of ratings is usually greater than 4 and not more than 9. On the one hand, the value of P is too large to be able to distinguish semantically, which makes it difficult to judge the classification of objects; on the other hand, the value of P is too small to meet the quality requirements of fuzzy comprehensive evaluation. In this study, we adopt five levels of fuzzy expression: high risk, high risk, medium risk, low risk and low risk.

(4) Fuzzy comprehensive evaluation

Because the factors at each level are determined by the factors at the lower level, the single factor evaluation of a factor at the s level should be the result of the comprehensive evaluation of the factors at the lower level t. After synthesizing the multi-factor evaluation matrix

$$R_i = \begin{bmatrix} r_{i11} & a_{i12} & \cdots & r_{i1p} \\ r_{i21} & r_{i22} & \cdots & r_{i2p} \\ \vdots & \vdots & \vdots & \vdots \\ r_{in1} & r_{in2} & \cdots & r_{inp} \end{bmatrix}$$

of level t with the corresponding weight of level t factor, the fuzzy comprehensive evaluation set

$$B_i = A_i \circ R_i = [a_{i1}, a_{i2}, \ldots a_{in}] \circ \begin{bmatrix} r_{i11} & a_{i12} & \cdots & r_{i1p} \\ r_{i21} & r_{i22} & \cdots & r_{i2p} \\ \vdots & \vdots & \vdots & \vdots \\ r_{in1} & r_{in2} & \cdots & r_{inp} \end{bmatrix}$$

of a factor of level s can be obtained, in which Ai is the vector representing the weight of level t factor.

The judgment matrix of spacecraft assembly process parameters V1～V5 is shown in Table 4.

Table 4. Parameter V1～V5 Judgment Matrix (filled by experts).

| | Operator V1 | Operating object V2 | Operating environment V3 | Operational type V4 | Process method V5 |
|---|---|---|---|---|---|
| Operator V1 | 1 | 1/3 | 1/3 | 1 | 5 |
| Operating object V2 | / | 1 | 1 | 3 | 7 |
| Operating environment V3 | / | / | 1 | 3 | 7 |
| Operational type V4 | / | / | / | 1 | 5 |
| Process method V5 | / | / | / | / | 1 |

*4.3. Comprehensive evaluation results based on membership degree*

Because there are many parameters involved in assembly safety evaluation, this paper takes the calculation of operator's parameter V1 as an example to illustrate the calculation method of the corresponding risk grade membership degree of each parameter.

(1) Applying AHP method and using expert scoring method to determine the weight coefficients, the weights of the parameters V11, V12, V13 and V14 of the third layer are obtained, which constitute the matrix WC1 of one row and four columns.

(2) Determine the criteria for determining the parameters V11, V12, V13 and V14 corresponding to the five grades in the alternative level, as shown in Table 5.

(3) By comparing the information collected from the questionnaire of parameter V1 with the criteria shown in table 5, the membership degrees of risk levels of parameters V11, V12, V13 and V14 can be calculated respectively, and the membership matrix RC1 of four rows and five columns can be constructed.

(4) The membership degree RB1=WC1·RC1 of each risk grade of the second layer parameter V1 is calculated.

By the same method, the membership degree of V1～V5 risk grade can be obtained.

According to the calculation method of parameters in the previous section, the membership degree of the second level parameters V1, V2, V3, V4 and V5 risk levels is obtained, and the membership matrix RB= [RB1, RB2, RB3, RB4, RB5] $^{T}$ of five rows and five columns is constructed.

Using AHP method, the weight coefficients of the five parameters in the second layer are determined by expert scoring and normalized to form a matrix WB of one row and five columns.

By multiplying the weight coefficient matrix with the membership degree matrix of each factor's risk grade, the membership degree RA=WB·RB of the risk grade of the first layer parameter (i.e. the top layer parameter) can be obtained.

According to the principle of maximum membership degree, the risk level corresponding to the largest of the five values corresponding to the first (top) membership degree is the result of comprehensive risk assessment.

Table 5. Criteria for Determining Parameters V11～V14.

| parameter | Criteria for judgment (five-level scoring system) | | | | | |
|---|---|---|---|---|---|---|
| | Input condition | Decision result | | | | |
| | | High risk | Higher risk | At risk | Lower risk | Low ris |
| Number V11 | 1 people | | | | | √ |
| | 2~3 people | | | | √ | |
| | 4~5 people | | √ | | | |
| | More than 5 people | √ | | | | |
| Continuous operation time V12 | More than 2 hours | √ | | | | |
| | 1~2 hours | | √ | | | |
| | 0.5~1 hour | | | √ | | |
| | Less than 0.5 hours | | | | √ | |
| Operational Attitude V13 | Low comfort | √ | | | | |
| | Lower comfort | | √ | | | |
| | Comfort level | | | √ | | |
| | Higher comfort | | | | √ | |
| | High comfort | | | | | √ |
| Collaboration Mode V14 | Interdepartmental | | √ | | | |
| | Single sector | | | | √ | |

Applying the safety evaluation model of assembly, we can synthetically analyse each single factor in the process of spacecraft assembly, and get the high-risk operation object. We can take further risk control measures for the high-risk object, so as to eliminate the risk, reduce the risk or control the risk, and improve the safety of the assembly process.

## 5. Validation of safety evaluation methods

A total of 138 work items are included in the technical process of a certain type of assembly process. After evaluating by applying the safety evaluation model of the assembly process, the risk values of all projects are obtained. The statistical results are shown in Table 6. The results are accurate and effective, and the risk identification is in place.

Table 6. Safety evaluation results of a certain type of assembly process.

| Serial number | Value at risk | Number | Proportion |
|---|---|---|---|
| 1 | High risk | 20 | 14.49% |
| 2 | Higher risk | 24 | 17.39% |
| 3 | At risk | 28 | 20.29% |
| 4 | Lower risk | 11 | 7.97% |
| 5 | Low risk | 55 | 39.86% |

## 6. Concluding remarks

Based on the analysis and identification of risk factors, this study establishes a safety evaluation model for spacecraft assembly process, further investigates related safety evaluation methods, completes the framework and calculation of evaluation methods, and ensures the accuracy and objectivity of evaluation results. Finally, through the example verification of a certain model, the evaluation results are in good agreement with the experience, high discrimination, and good results have been achieved. Through the application of this evaluation model in practical work, the risk factors are effectively identified, and the risk of damage to the key parts of spacecraft in the assembly stage is reduced, which provides a strong guarantee for reducing the frequency of quality and safety problems and the "zero defect" of model quality.

The popularization and application of this study will greatly reduce the risk of damage to the key parts of spacecraft in the assembly stage, thus avoiding the direct economic losses caused by damage to key products and the indirect economic losses caused by delayed development progress, and will greatly reduce the frequency of quality and safety problems, thus increasing the quality of the group company and the China Institute of Space Technology. Brand value will greatly reduce the probability of quality and safety problems in assembly production and guarantee the quality and progress of spacecraft assembly development. It will win a good reputation and reputation for the group company and our institute in the international and domestic society, and to a certain extent enhance the influence and competitiveness of the group company and the Fifth Academy in the international aerospace market and domestic aerospace mission bidding.

## References

[1] Wang M.Z. (2008). Assembly process of steel wire screw sleeve in satellite assembly. Spacecraft environmental engineering. 25(6): 598-600.
[2] Yi W.M, Li Q, Liu H.Y, Sun G. (2008). Study on Electrostatic Protection during Satellite Assembly. Spacecraft Environmental Engineering. 25 (4): 387-390.
[3] Liu Y.G. (2004). Technological Improvement of the Assembly Scheme of a Satellite Whole Star Crane. Spacecraft Environmental Engineering. 21 (4): 48-53.
[4] Huang J, Shen X.H. (2009). Risk Analysis and Control Strategy Research in Satellite Assembly Process. Quality and Reliability. (3): 112-116

[5] Yang Y T, Wei T C and Wang Y H. (2010) Numerical study of turbulent slot jet impingement cooling on a semi-circular concave surface. International Journal of Heat and Mass Transfer 54:482-489
[6] Mosneron D, Reer B, Heslinga G. (1997). Reliability Engineering and System Safety. JOHN WILEY & SONS, INC. 58:249-274
[7] Huang C H, Chen Y H and Li H Y. (2013). International Journal of Heat and Mass Transfer. Reliability Engineering and System Safety. 31:992-1006