Quality prediction and control of cable harness wiring using extension theory and a backpropagation neural network

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Abstract
Given that the cable harness wiring quality (CHWQ) of complex mechatronic products is affected by multiple factors and it is difficult to solve the resulting control problems, this paper proposes a quality prediction method for cable harness wiring using extension theory and a backpropagation (BP) neural network. First, a quality prediction framework is designed based on the factors influencing the composition and analysis of the CHWQ. Second, we establish a quality evaluation index system based on five aspects and design a first-level factor set and a second-level factor set. Based on the single factor index for various parameters and evaluation of data after dimensionless parameter processing, we use extension theory and the entropy weight method to determine the membership matrix and the fuzzy weight vector for the first-level evaluation. Additionally, the single factor and the synthetic fuzzy weight vector are determined using the entropy weight method and the analytic hierarchy process (AHP), respectively, and quality grade evaluation based on the fuzzy synthetic evaluation (FSE) method is completed. Finally, we use a three-layer feedforward neural network to predict the quality status of a specific phased array radar system. The results demonstrate that the proposed method can produce increased prediction accuracy.

Keywords
Cable harness wiring quality, CHWQ, quality prediction, quality control, extension theory, BP neural network, fuzzy synthetic evaluation

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Introduction
A cable harness generally consists of cables, connectors and sheaths.¹ Cable harnesses are widely used in complex mechatronic products to connect different items of electronic equipment and must therefore meet specific electrical and mechanical requirements.¹–³ As an energy and signal transmission medium, the cable harness is playing an increasingly important role in complex mechatronic products for applications such as airplanes, satellites, radar and shipping equipment. However, it is challenging for designers to improve cable harness quality while also accommodating the following wide range of strict constraints:³

(1) The wiring space for the cable harness is very small within the narrow assembly spaces of these complex mechatronic products;

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The cable harness wiring must have sufficient electromagnetic compatibility to prevent production of electromagnetic interference;

(3) The wiring path of the cable harness must be well designed to avoid self-collisions and prevent collisions between different cable harnesses;

(4) Some of these products have to work in complex environments with conditions such as high humidity and high operating temperatures;

(5) The feasibility of wiring the cable harness may decrease because of the complexity of these products.

The quality of cable harness wiring is an important factor in comprehensive assessment of the performance and reliability of products and is affected by multiple factors but the research on wiring quality trend analysis is comparatively inadequate. This paper proposes a quality prediction and control method for cable harness wiring that uses extension theory and a backpropagation (BP) neural network. The proposed approach involves the following steps and contributions. (1) A quality prediction framework is designed for cable harness wiring based on the factors influencing the composition and analysis of the cable harness wiring quality (CHWQ). The research in this article basically revolves around this framework. (2) Based on the introduction of extension theory, the membership matrices for the assessment are established using extension theory and the entropy weight method. These matrices are realized to establish quality grade assessment of the cable harness wiring based on fuzzy synthetic evaluation (FSE) in combination with the analytic hierarchy process (AHP) method. (3) To predict the wiring quality, this paper uses a BP neural network as a prediction method by using the sequence values from the FSE as the inputs to the neural network. Some specific CHWQ control measures are then given upon analysis of the prediction results.

The rest of this paper is organized as follows. Section 2 briefly reviews some of the existing work related to this research. Factors influencing the composition and analysis of the CHWQ are presented in Section 3. Section 4 illustrates the CHWQ prediction method in detail. Section 5 presents a case study based on the proposed approach and provides specific quality control measures. Finally, conclusions are drawn from the research in Section 6.

State of the art

This section provides a brief background description of the relevant work in the fields of wiring technology and quality prediction and control methods. To date, several studies have focused on routing and assembly planning for cable harnesses. Ritchie et al. studied the effectiveness of the use of immersive virtual reality in the design and routing of cable harnesses for enhancement of the expertise of the cable harness designer and also developed a new virtual cable design system for cable harness assemblies. Conru described a system for automatic routing of cable harnesses in 3D environments that used a pair of genetic algorithms. The cable harness routing problem was decomposed into two problems: generation of a harness configuration (topology) and routing of the harness in the environment. Van der Velden et al. discussed the development of an intelligent routing system to automate the design of electrical wiring harnesses and pipes in aircraft. Hermansson et al. presented a novel method to automatically plan and determine smooth and collision-free mounting of connectors in a wiring harness installation. The research described above has provided some meaningful methods for cable harness design and assembly. However, these researchers rarely concentrated on analysis of the assembly quality trends and early wiring quality prediction and warnings for the cable harness.

Mazzuchi et al. discussed the results of an actual experiment in which the paired-comparison technique for expert judgment was used to develop a relationship for the wire failure probability as a function of the influential factors in an aircraft environment. To control and evaluate the quality of the Cu wire bonding process, Tsai proposed an adaptive diagnosis system using grey relational analysis (GRA) and a neurofuzzy technique. Ertugrul and Guenes proposed a fuzzy quality control chart to monitor the product quality characteristics or the quality parameters of manufacturing processes using traditional control charts. With the aim of resolving the difficulties in the evaluation and provision of early warning of quality loss in key assembly process materials for complex electromechanical products, Yin et al. proposed an evaluation and early warning method that integrated real-time field acquisition of abnormal quality information with a comprehensive evaluation and early warning of the quality loss.

From the analysis above, although some researchers have made meaningful contributions on early warning and control of quality, most of the previous research was conducted for rigid structures rather than for a flexible cable harness. The quality prediction and control processes for cable harness wiring are often more difficult to perform than those for rigid structures because of the flexible characteristics of the cable harness and the complexity of its installation. This paper is intended to provide a new quality prediction method for flexible cable harness wiring.
Composition and analysis of influencing factors

The factors that influence the quality of cable harness wiring have complex and changeable characteristics. When a particular phased array radar device (i.e. the antenna array device) is taken as an example, the factors influencing the quality mainly include:

1) **Complex structure with narrow and small wiring space.** The complete antenna array device contains a large number of electronic components, e.g., power modules, manipulation modules, display modules, cable harness plug-in cards, fixed brackets and fixed convex platforms. These internal electronic parts and components cause the available wiring space to be irregular and narrow.

2) **Flexible features, leading to easily changed shape and location.** Unlike rigid bodies, the flexible features of cable harnesses mean that their deformation and spatial positioning can change easily under the influence of the drag force that occurs during the wiring process. A deformed cable harness will present wriggling, winding, and snarling behavior, along with other complex geometries. It is thus difficult to determine the spatial attitude, direction, length, and location relationships for the cable harness.

3) **Large quantities, wide component varieties and complex installation processes.** The number of cable harnesses contained in a complete antenna array device can reach a high total value in the thousands. In addition, the different types of cable harness required (e.g. single core, multi-core, flat; rigid, semi-rigid, flexible; low frequency, intermediate frequency, high frequency; large wire diameter corners, small wire diameter corners) will have different operating characteristics. The installation processes for these cable harnesses are then much more complex.

4) **More detected contents, large quantities of information, and deviations existing in the data processing.** The on-line testing and detection of the cable harness involves a number of processes, e.g. conduction testing, resistance capacitance testing, circuit breaker testing, insulation testing, and compression testing. This can lead to large quantities of information or data being acquired. The results may also show inevitable deviations from the required values when the data are processed.

Despite the analysis above, the quality of the cable harness wiring can be affected by multiple factors. In addition to the four main factors listed above, the CHWQ can also be affected by the operating proficiency of the wiring workers, the degree of wiring requirements from an overall viewpoint, and the workshop’s environmental conditions (where the temperature and humidity are extremely important for sophisticated precision equipment).

Quality prediction method

Framework of the method

To enhance the quality of cable harness wiring for complex mechatronic products, a quality prediction framework is designed for cable harness wiring that is illustrated in Figure 1.

1) Phase I: Preparations before cable harness wiring. This phase mainly involves preparation of the resources required to perform the wiring process. Adequate preparations of the various resources described above provide a good foundation for smooth development of the subsequent wiring works.

2) Phase II: Wiring by experienced workers. In this phase, the wiring workers use the resources offered in Phase I to complete the wiring task based on their accumulated experience. During the wiring process, the workers should comply with certain wiring specifications, such as cable harness selection principles, classification of the electrical components, and fixed cable harness wiring methods.

3) Phase III: Quality assessment after the cable harness wiring procedure. After wiring, the product cannot be used immediately. In this phase, a variety of test instruments are required to test the cable harness on-line and obtain multiple types of working state data. Using data processing techniques, the required indicators are extracted for use in the quality assessment. In addition, the FSE method is used to complete the wiring quality assessment procedure. This phase is the core content of this paper and will be explained in greater detail in the following.

4) Phase IV: Quality prediction. During this phase, the results acquired from the FSE method in Phase III are used as the input to the neural network training model. The trained neural network model is then used to predict the new FSE value for the phased array radar cable harness wiring. Based on the predicted FSE value, the quality grade of the cable harness wiring can then be determined. Finally, decision recommendations are made based on the quality grade.

5) Phase V: Corresponding corrective action program based on the decision recommendations.
Other possible problems can be determined via judgment of the wiring status of the equipment as a whole (including the extension modules). The wiring requirements are met if no problems exist (meaning that the wiring quality is “Good”); otherwise, professional knowledge is used to evaluate the seriousness of any problems that do exist according to the results (meaning that the wiring quality is “Fine”, “Ordinary” or “Poor”).

Figure 1. Quality prediction framework for cable harness wiring.
Quality prediction method

Extension theory. Extension theory is a new type of knowledge system based on the concepts of matter elements and extension sets and was proposed by the Chinese researcher Cai in 1983. In a defined universe, the associated function value can quantitatively describe the changes in the relationships between each multi-dimensional matter element and each extension set and, on the basis of a correlation degree analysis, can distinguish different levels and allow upward range expansion to be realized. Extension theory can deal with any incompatibility issues and can express the features of the objective by building a matter element evaluation model. Extension theory has been widely used in various fields. In this paper, we use the extension theory method to study the wiring quality assessment.

Fuzzy synthetic evaluation model. In the FSE method, the weighted vector determines the classification via a matrix operation and the fuzzy evaluation matrix can be established after all individual membership functions of the evaluated factors have been determined. Figure 2 shows the FSE model of the CHWQ.

A) Determination of the evaluation set and the factor set

To evaluate the quality grade of the cable harness wiring for complex mechatronic products, we establish an evaluation set $V = \{ \text{Good, Fine, Ordinary, Poor} \}$ to represent the four grades of the wiring quality. To enable analysis and clarify the different quality levels that reflect the severity of the problem, some descriptions of the quality grades are specified in Table 1.

In this paper, on the basis of the characteristics of the complex mechatronic products and the factors influencing the composition and the quality of the wiring, we establish a quality evaluation index system for cable harness wiring based on the following five aspects: (a) mechanical performance; (b) electrical performance; (c) wiring process; (d) spatial arrangement; (e) environmental status.
performance; (c) wiring process; (d) spatial arrangement; and (e) environmental status. The first-level factor set is 
\[ X = \{X_1, X_2, X_3, X_4, X_5\} \]
and 
\[ X_i = \{x_{i1}, x_{i2}, \ldots, x_{in}\} \]
is the second-level factor set, where 
\[ i = 1, 2, \ldots, 5. \]
The quality grade evaluation factor set for the cable harness wiring is determined accordingly and is shown in Figure 3.

- **Mechanical performance factors** \( X_1 \): minimum bending radius \( x_{11} \), cable harness bending stress \( x_{12} \), cable harness thermal strain \( x_{13} \), cable harness thermo-mechanical stress \( x_{14} \).
- **Electrical performance factors** \( X_2 \): electromagnetic compatibility \( x_{21} \), coupling crosstalk degree among cable harness wires \( x_{22} \), stray electromagnetic field intensity \( x_{23} \).
- **Wiring process factors** \( X_3 \): colligation process \( x_{31} \), protective process \( x_{32} \).
- **Spatial arrangement factors** \( X_4 \): equipment maintainability \( x_{41} \), overall aesthetic property \( x_{42} \).
- **Environmental status factors** \( X_5 \): wiring environment temperature \( x_{51} \), wiring environment humidity \( x_{52} \).

**B) First-level fuzzy synthetic evaluation**

a. **Establishment of membership matrixes**

Before carrying out the first-level FSE (single factor fuzzy evaluation) for the second-level factor set 
\[ X_i = \{x_{i1}, x_{i2}, \ldots, x_{in}\} \]
\[ i = 1, 2, \ldots, 5 \]
we must first determine the first-level fuzzy weight vectors \( A_i \) and the membership matrices for the first-level FSE \( M_i \). Here we introduce the extension method to establish the membership matrixes.

Extension theory primarily contains a matter element and an extension set. The matter element researches the models and their transformations and the nature of the matter can then be represented easily. In the designed correlation functions, the extension set can express the degree of correlation between two matter elements and also serves as the quantitative index of the extension theory. Based on the method described above, the degree of membership of the evaluation set can be determined more comprehensively for each factor. To describe this, we use a matter element in this paper, and the ordered triad of this element can be expressed as:

\[ R = (N, C, V) \]

where \( N \) represents the matter, \( C \) represents the characteristics, and \( V \) represents \( N \)'s measure based on the characteristics \( C \). Assuming that \( R = (N, C, V) \) is a multidimensional matter element, \( C = (c_1, c_2, \ldots, c_n) \) is a
characteristics vector and $V = (v_1, v_2, \cdots, v_n)$ is a value vector of $C$, then a multidimensional matter element can be defined as:\cite{25}

$$
R = (N, C, V) = \begin{bmatrix}
R_1 \\
R_2 \\
\vdots \\
R_n
\end{bmatrix} = \begin{bmatrix}
N & c_1 & v_1 \\
& c_2 & v_2 \\
& \vdots & \vdots \\
& c_n & v_n
\end{bmatrix}
$$

(2)

where $R_i = (N_i, c_i, v_i), (i = 1, 2, \cdots, n)$ is the sub-matter element of $R$.

The steps for determination of the membership matrixes based on extension theory are detailed as follows.

**Step 1: Dimensionless parameters**

The dimensionality of each parameter in the factor set is different and incommensurability issues thus exist, so it is necessary to perform dimensionless processing of the various parameters and remove the dimensional effects among the indicators through a numerical transformation. The dimensionless parameters can be calculated using equation (3) as follows:

$$
v_k = \begin{cases}
\frac{\hat{v}_k - \min(\hat{v}_k)}{\max(\hat{v}_k) - \min(\hat{v}_k)}, & \text{the bigger the better parameters (Benefit Type)} \\
\frac{\max(\hat{v}_k) - \hat{v}_k}{\max(\hat{v}_k) - \min(\hat{v}_k)}, & \text{the smaller the better parameters (Cost Type)}
\end{cases}
$$

(3)

where $\hat{v}_k$ and $v_k$ are the values of the $k$th ($k = 1, 2, \cdots, 13$) parameter before and after dimensionless parameter processing, respectively. Additionally, $\max(\hat{v}_k)$ and $\min(\hat{v}_k)$ are the maximum and minimum values of the $k$th ($k = 1, 2, \cdots, 13$) parameter before and after dimensionless parameter processing, respectively.

**Step 2: Confirming the classical field**

Equation (4) is used to express the classical field as follows:

$$
R_{i}^{(j)} = (N_i, C_i, V_i) = \begin{bmatrix}
N_{ij} & c_{i1} & \langle a_{0j1}, b_{0j1} \rangle \\
& c_{i2} & \langle a_{0j2}, b_{0j2} \rangle \\
& \vdots & \vdots \\
& c_{in} & \langle a_{0jn}, b_{0jn} \rangle
\end{bmatrix}
$$

(4)

where $R_{i}^{(j)} (i = 1, 2, \cdots, 5)$ is a matter element; $N_{ij} (j = 1, 2, 3, 4)$ represents the $i$th evaluation category; $C_i$ is the $i$th evaluation indicator; and $V_i$ is the $C_i$ value used to provide scope, i.e. in the classical domain, 

$$
V_{0jk} = (a_{0jk}, b_{0jk}) (k = 1, 2, \cdots, n_i).
$$

**Step 3: Confirming the joint field**

Equation (5) is used to express the joint field as follows:

$$
R_p^{(i)} = (P, C_i, V_p) = \begin{bmatrix}
P & c_1 & \langle a_{p1}, b_{p1} \rangle \\
& c_2 & \langle a_{p2}, b_{p2} \rangle \\
& \vdots & \vdots \\
& c_n & \langle a_{pn}, b_{pn} \rangle
\end{bmatrix}
$$

(5)

where $P$ represents all the evaluations of the CHWQ; $V_{pk}$ represents the value of $P$ and its spanned scope, which is called $P$’s joint field, is $c_k (k = 1, 2, \cdots, n_i)$.

**Step 4: Confirming the evaluated matter element**

To evaluate the CHWQ grade, we can represent the data sets on the basis of the matter element, and the evaluated matter element $R$ can be expressed as:

$$
R = (p, C_i, V_i) = \begin{bmatrix}
p & c_1 & v_1 \\
P & c_2 & v_2 \\
P & \vdots & \vdots \\
P & c_n & v_n
\end{bmatrix}
$$

(6)

where $V_i$ represents the value scope of $p$.

**Step 5: Confirming the correlative degree of each factor index**

The correlative degree of each factor index can be expressed as:

$$
m_{ij}^{(i)} = \begin{cases}
\frac{\rho_i(v_{mk}, v_{0jk})}{\rho_i(v_{mk}, v_{0jk}) - \rho_i(v_{mk}, v_{pk})}, & v_{mk} \not\in v_{0jk} \\
-\rho_i(v_{mk}, v_{0jk}), & v_{mk} \in v_{0jk}
\end{cases}
$$

(7)

where

$$
\rho_i(v_{mk}, v_{0jk}) = \left| \frac{v_{mk} - \frac{a_{0jk} + b_{0jk}}{2}}{b_{0jk} - a_{0jk}} \right|
$$

(8)
The membership matrix of the first-level FSE $M_i$ can then be expressed as:

$$M_i = (m_{ij})_{n_i \times 4} = \begin{bmatrix} m^{(i)}_{11} & m^{(i)}_{12} & m^{(i)}_{13} & m^{(i)}_{14} \\ m^{(i)}_{21} & m^{(i)}_{22} & m^{(i)}_{23} & m^{(i)}_{24} \\ \vdots & \vdots & \vdots & \vdots \\ m^{(i)}_{n_i1} & m^{(i)}_{n_i2} & m^{(i)}_{n_i3} & m^{(i)}_{n_i4} \end{bmatrix}$$

\[(10)\]

b. Entropy weight determination method for single factor vector

The weight reflects the degree of importance of the various parameters on the evaluation target and is related directly to the credibility of the evaluation results. Determination of the weight is a core problem when performing a comprehensive evaluation. However, when applying the FSE method to the CHWQ assessment, the scientific features of the weight value usually have some ambiguity and some important information is lost when the method emphasizes extreme value action. Additionally, the weight value often includes indicator information and there is no relationship among the assessment objects. Therefore, the information entropy has been introduced to solve the problems described above. The information entropy can measure the amount of valuable information based on the adopted data. For the same indicator, the entropy value is determined by whether the difference between the evaluation objects is large or small. If the difference is large, then the entropy is small, and the indicator’s weight should be set to be relatively large in this case. In contrasting case where the entropy is large, the weight would be small. Therefore, use of the theory of entropy to determine the weight is reasonable.

The steps of the entropy weight determination method for the single factor fuzzy weight vectors are described as follows.

**Step 1: Normalized processing of the judgment matrix**

Assuming that there are $m$ (in this paper, $m = 4$, as shown in Table 1) different quality grades in the wiring quality evaluation model, each indicator category contains $n_i$($i = 1, 2, \ldots, 5)$ factors. In this paper, there are five categories. The judgment matrix is constructed and is denoted by $P_i$, where $P_i$ is the transpose of the membership matrix $M_i$, i.e. $(P_i = (p_{ij}^{(i)}) = M_i^T, j = 1, 2, \ldots, m; k = 1, 2, \ldots, n_i)$. Normalized processing of $P_i$ is then performed and the judgment matrix is denoted by $P_i$ after the normalization.

**Step 2: Definition of the entropy**

Let $x_{ik}$ be the $k$th factor of the $i$th category indicator, where $i = 1, 2, \ldots, 5; k = 1, 2, \ldots, n_i$. The entropy $e_k^{(i)}$ of each factor $x_{ik}$ is then defined as:

$$e_k^{(i)} = -u \sum_{j=1}^{m} (f_j^{(i)} \ln f_j^{(i)})$$

in which $f_j^{(i)} = \hat{p}_{jk}^{(i)} / \sum_{j=1}^{n_i} \hat{p}_{jk}^{(i)}$ and $u = 1 / \ln m$. When $f_j^{(i)} = 0, f_j^{(i)} \ln f_j^{(i)} = 0$, $j = 1, \ldots, m$.

**Step 3: Definition of the weight of entropy**

The weight of entropy of the $x_{ik}^{(i)}$th factor can be defined as:

$$w_k^{(i)} = \frac{1 - e_k^{(i)}}{n_i \sum_{k=1}^{n_i} e_k^{(i)}}$$

where $0 \leq w_k^{(i)} \leq 1$ and $\sum_{k=1}^{n_i} w_k^{(i)} = 1$.

**Step 4: Definition of the first-level fuzzy weight vector**

Using the weight of entropy $w_k^{(i)}$, the first-level fuzzy weight vector $A_i$ can be expressed as:

$$A_i = [w_1^{(i)}, w_2^{(i)}, \ldots, w_n_i^{(i)}]$$

\[(13)\]

c. Fuzzy evaluation of single factor

On the basis of the preceding calculation steps, i.e. Steps 1 to 4, we use the weighted average algorithm to synthesize the arithmetic for the membership matrix $M_i$ and the single factor fuzzy weight vector $A_i$ and then obtain the FSE model $B_i$ of the $i$th ($i = 1, 2, \ldots, 5$) category indicator:

$$B_i = A_i \cdot M_i$$

\[(14)\]

**C) Second-level fuzzy synthetic evaluation**

a. AHP determination method for the comprehensive fuzzy weight vectors

The AHP method is mainly used to solve multiple criteria decision issues in which the criteria are compared pair-wise based on their importance. The steps by which AHP is used to determine the synthetic fuzzy weight vectors $A$ are described as follows (to obtain the solutions for the maximum characteristic root and the corresponding eigenvectors of the judgment matrix, the square root method is used in this paper).

Step 1: Construct the judgment matrixes

For the first-level factor set of the hierarchy structure model (i.e., the quality grade evaluation factor set for the cable harness wiring) $X = \{X_1, X_2, X_3, X_4, X_5\}$, a rating scale (1–9 scale in the traditional AHP method) is used to construct the judgment matrixes:

$$D = (d_{ij})_{n \times n} \quad (15)$$

Step 2: Calculate the product of each row element for the judgment matrix $D$, i.e.

$$H_i = \prod_{j=1}^{n} d_{ij}, i = 1, 2, \cdots , n \quad (16)$$

Step 3: Calculate the $n$th roots of $H_i$, i.e.

$$W_i = \sqrt[n]{H_i}, (i = 1, 2, \cdots , n) \quad (17)$$

Step 4: Perform normalization processing of the vector $W = [W_1, W_2, \cdots, W_n]^T$:

$$W_i = \frac{W_i}{\sum_{j=1}^{n} W_j}, (i = 1, 2, \cdots , n) \quad (18)$$

Step 5: Calculate the maximum characteristic root $\lambda_{\text{max}}$, i.e.

$$\lambda_{\text{max}} = \frac{1}{n} \sum_{i=1}^{n} \frac{(DW)_i}{W_i} \quad (19)$$

where $(DW)_i$ represents the $i$th component of the vector $DW$ and $W = [W_1, W_2, \cdots, W_n]^T$.

Step 6: Perform a consistency inspection of the judgment matrix

The value $d_{ij}$ in the judgment matrix $D$ reflects the ratio of the importance between factor $i$ and factor $j$. To determine whether the judgment matrix constructed by the cable harness wiring experts and using the experience of the operating personnel based on the 1 to 9 scale method is accepted, we need to perform a consistency inspection. The specific formulas used are given as follows:

$$CI = \frac{\lambda_{\text{max}} - n}{n - 1}, CR = \frac{CI}{RI} \quad (20)$$

where $CI$ is the consistency index, $n$ is the order of the judgment matrix, $CR$ is the consistency ratio, and $RI$ is the random consistency index $^{29}$ (see Table 2).

In general, the comparison matrix $D$ is of acceptable consistency if $CR < 0.1$. In some cases, $^{29}$ the consistency ratio is required to be less than 5% for $n = 3$ and less than 8% for $n = 4$.

b. Second-level FSE model

The first-level fuzzy evaluation results constitute the membership matrix $M$. When this matrix is combined with the second-level fuzzy weight vector $A$, the second-level fuzzy evaluation can be realized based on the weighted average operation performed for the first-level factor set $X = \{X_1, X_2, X_3, X_4, X_5\}$. The second-level FSE model is given by:

$$B = A \cdot M = A \cdot [B_1 \quad B_2 \quad B_3 \quad B_4 \quad B_5]^T \quad (21)$$

Quality prediction based on BP neural network

A) BP neural network model

It has been proved in theory that, when the transfer function of the hidden layer neurons is a bounded monotonically increasing continuous function, the three layers of a feedforward neural network can approximate a differentiable function with arbitrary precision, so this model is selected for the three-layer BP neural network model to forecast the CHWQ. The model consists of an input layer, a hidden layer and an output layer, and is shown in Figure 4.

Neurons are necessary for prediction of the quality of the cable harness wiring when using the BP neural network approach. When the inputs $x_i (i = 1, \cdots, m)$ are set, the weighted input $u$ can then be generated by calculating the linear combination of these inputs using the weights $\omega_i$, and $u$ can then be formulated as $^{30}$

$$u = \sum_{i=1}^{m} \omega_i x_i + \theta \quad (22)$$

| $n$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|-----|---|---|---|---|---|---|---|---|---|----|
| RI  | 0 | 0 | 0.52 | 0.89 | 1.11 | 1.25 | 1.35 | 1.40 | 1.45 | 1.49 |
where $X = (x_1, x_2, \ldots, x_m)^T$ represents the input neurons; $W = (\omega_1, \omega_2, \ldots, \omega_m)^T$ represents the weights; $\theta$ represents the threshold value and $u$ represents the weighted input.

Before the BP neural network model can be applied, the input and output variables must first be determined. In this paper, the input variables are specified as the previous five evaluation values of the quality grades of the FSE. The number of hidden layer nodes determines the network complexity and the nonlinear processing ability; the node number is generally determined based on experience gained from previous designs in combination with practical problems to be solved in tests, where too many or too few nodes will affect the network performance of the model. The number of hidden layer nodes can be obtained within an approximate range using the following empirical formula:

$$n = \sqrt{n_i + n_o} + a, \quad a \in [1, 10]$$  \hspace{1cm} (23)

where $n$ is the number of hidden layer nodes, $n_i$ is the input node number and $n_o$ is the output node number. From equation (23), we know that the hidden layer contains 12 neurons and the output layer then contains only 1 neuron, i.e. the predictive value of CHWQ. The BP neural network model for quality prediction of cable harness wiring is shown in Figure 5.

Here, the continuously differentiable log-sigmoid function, which we used as the activation function, can be defined as shown in equation (24):

$$f(x) = \frac{1}{1 + e^{-x}}$$  \hspace{1cm} (24)

In practical engineering applications of the BP neural network method, the numerical optimization performances of the training algorithms used are highly important. Different BP neural networks can be specified in terms of their error backpropagation algorithm; in this paper, the Levenberg–Marquardt (LM) algorithm is adopted and is used to solve for the second derivative of the error to judge the error rate of decline, to adjust the learning rate adaptively and to train the neural network to realize rapid convergence.

B) Network weight and threshold

Let the input vector be $x \in \mathbb{R}^5, x = (x_1, x_2, x_3, x_4, x_5)^T$, let the hidden layer contain 12 neurons where $u \in \mathbb{R}^{12}, u = (u_1, u_2, \ldots, u_{12})^T$, and let the output layer contain only one neuron $y$. Let the number of input learning samples be $Q$, where the corresponding desired outputs of $x_1, x_2, \ldots, x_Q$ are denoted by $t_1, t_2, \ldots, t_Q$, respectively. Let $w_j^i(j = 1, 2, \ldots, 12)$ be the weights from the hidden layers to the output layer, and let $w_k^i(k = 1, 2, \ldots, 5)$ be the weights from the input layers to the hidden layers. The outputs of each neuron are then given by:

$$y = f \left( \sum_{i=1}^{12} w_j^i u_j \right)$$  \hspace{1cm} (25)

$$u_j = f \left( \sum_{k=1}^{5} w_k^i x_k \right)$$  \hspace{1cm} (26)

Learning is performed for the $Q$ samples and the total error is:

$$E_t = \frac{1}{2} \sum_{i=1}^{Q} (t_i - y_i)^2$$  \hspace{1cm} (27)

Each weight is then adjusted and the computation formula for the weight adjustment is given as follows:

$$w_j^i(h_0 + 1) = w_j^i(h_0) - \eta \frac{\partial E_t}{\partial w_j^i}$$  \hspace{1cm} (28)
where the number of iterations is $h$. If $E_r < \varepsilon$ (where $\varepsilon$ is a very small count), then learning is stopped.

### C) Quality prediction of cable harness wiring

The trained BP neural network can now be used to predict the FSE value of the CHWQ. On the basis of the previous discussion and analysis, the process for quality prediction of the cable harness wiring using the BP neural network method can be expressed as follows. \(^3\text{6}\)

**Case study**

**Quality prediction**

To introduce the FSE and perform quality prediction of the cable harness wiring, we use the cable harness wiring of a specific phased array radar system as an example. An extension module of the phased array radar is shown in Figure 6. In practical engineering, the wiring quality will affect the tactical technique index of the phased array radar directly. In phased array radar antenna design, the design of the antenna array wiring is a difficult process. If the wiring scheme is unreasonable, then the internal equipment installation and adjustment properties of the antenna array will be seriously affected and stress may appear around the cable harness junction. As a result, poor contact, short circuits, open circuits and other faults may occur if the stress is not eliminated, and the normal operation of the equipment would ultimately be affected. Figure 7 shows the topology of a cable harness structure.

We collected a set of wiring quality status data for phased array radar from the Nanjing Research Institute of Electronics Technology. The method proposed in this paper was then used to determine the membership degree of each factor relative to the evaluation set.
$V = \{\text{Good, Fine, Ordinary, Poor}\}$. The results are presented in Tables 3 to 7.

Based on the single factor index values of the various parameters and the evaluation of the data after the dimensionless processing stage, we use the extension theory and the entropy weight method described in this paper to determine the membership matrix and fuzzy weight vector for the first-level evaluation. The steps for the single-factor evaluation are detailed as follows (we use Table 3 as an example to introduce the procedure here).

**Table 3.** Single-factor index and FSE of mechanical performance.

| Factors | Good | Fine  | Ordinary | Poor   | Value for preparation of evaluation |
|---------|------|-------|----------|--------|-------------------------------------|
| $x_{1}^{(1)}$ | 0.620 – 1.00 | 0.352 – 0.620 | 0.280 – 0.352 | 0.00 – 0.280 | 0.547 |
| $x_{2}^{(1)}$ | 0.655 – 1.00 | 0.380 – 0.655 | 0.251 – 0.380 | 0.00 – 0.251 | 0.694 |
| $x_{3}^{(1)}$ | 0.740 – 1.00 | 0.317 – 0.740 | 0.223 – 0.317 | 0.00 – 0.223 | 0.678 |
| $x_{4}^{(1)}$ | 0.710 – 1.00 | 0.230 – 0.710 | 0.171 – 0.230 | 0.00 – 0.171 | 0.585 |

FSE: fuzzy synthetic evaluation.

**Table 4.** Single-factor index and FSE of electrical performance.

| Factors | Good | Fine  | Ordinary | Poor   | Value for preparation of evaluation |
|---------|------|-------|----------|--------|-------------------------------------|
| $x_{1}^{(2)}$ | 0.660 – 1.00 | 0.339 – 0.660 | 0.105 – 0.339 | 0.00 – 0.105 | 0.423 |
| $x_{2}^{(2)}$ | 0.825 – 1.00 | 0.416 – 0.825 | 0.292 – 0.416 | 0.00 – 0.292 | 0.875 |
| $x_{3}^{(2)}$ | 0.817 – 1.00 | 0.390 – 0.817 | 0.182 – 0.390 | 0.00 – 0.182 | 0.732 |

FSE: fuzzy synthetic evaluation.

**Step 1. Determine the classical field of the CHWQ status**

$$R_{01}^{(1)} = \begin{bmatrix}
\text{Good}, & c_{1}, & (0.620, 1.00) \\
\text{c_{2}}, & (0.655, 1.00) \\
\text{c_{3}}, & (0.740, 1.00) \\
\text{c_{4}}, & (0.710, 1.00) 
\end{bmatrix}$$

$$R_{02}^{(1)} = \begin{bmatrix}
\text{Fine}, & c_{1}, & (0.352, 0.620) \\
\text{c_{2}}, & (0.380, 0.655) \\
\text{c_{3}}, & (0.317, 0.740) \\
\text{c_{4}}, & (0.230, 0.710) 
\end{bmatrix}$$
Using the same steps, we can obtain the corresponding membership matrices for the values in Tables 4 to 7, and these matrices are listed as follows.

\[ M_1 = \begin{bmatrix} 0.100 & 0.620 & 0.280 & 0.000 \\ 0.080 & 0.600 & 0.300 & 0.020 \\ 0.130 & 0.740 & 0.120 & 0.010 \\ 0.060 & 0.710 & 0.230 & 0.000 \end{bmatrix} \]

\[ M_2 = \begin{bmatrix} 0.060 & 0.660 & 0.180 & 0.100 \\ 0.020 & 0.530 & 0.370 & 0.080 \\ 0.010 & 0.590 & 0.330 & 0.070 \end{bmatrix} \]

\[ M_3 = \begin{bmatrix} 0.030 & 0.550 & 0.380 & 0.040 \\ 0.020 & 0.570 & 0.400 & 0.010 \end{bmatrix} \]

\[ M_4 = \begin{bmatrix} 0.090 & 0.700 & 0.200 & 0.010 \\ 0.070 & 0.730 & 0.180 & 0.020 \end{bmatrix} \]

\[ M_5 = \begin{bmatrix} 0.770 & 0.200 & 0.030 & 0.000 \\ 0.750 & 0.180 & 0.060 & 0.010 \end{bmatrix} \]

**Step 5. Calculate the entropy value for each parameter**

Using equation (11), the entropy values of the various factors can be determined. Tables 8 to 12 show these entropy values.
Table 8. Entropy values for the mechanical performances of various factors.

| Factors | $x_1^{(4)}$ | $x_2^{(4)}$ | $x_3^{(4)}$ | $x_4^{(4)}$ |
|---------|-------------|-------------|-------------|-------------|
| Entropy: $e_k^{(4)}$ | 0.9872 | 0.9903 | 0.9758 | 0.7772 |

Table 9. Entropy values for the electrical performances of various factors.

| Factors | $x_1^{(2)}$ | $x_2^{(2)}$ | $x_3^{(2)}$ |
|---------|-------------|-------------|-------------|
| Entropy: $e_k^{(2)}$ | 0.9416 | 0.9818 | 0.9441 |

Table 10. Entropy values for the wiring processes of different factors.

| Factors | $x_1^{(3)}$ | $x_2^{(3)}$ |
|---------|-------------|-------------|
| Entropy: $e_k^{(3)}$ | 0.9843 | 0.9603 |

Table 11. Entropy values for the spatial arrangements of different factors.

| Factors | $x_1^{(4)}$ | $x_2^{(4)}$ |
|---------|-------------|-------------|
| Entropy: $e_k^{(4)}$ | 0.9872 | 0.9903 |

Step 6. Determination of the first-level fuzzy weight vectors

When the entropy values are determined, the first-level fuzzy weight vectors $A_i (i = 1, 2, \ldots, 5)$ can be established using equations (12) and (13), and the results are given as follows:

$A_1 = [0.3766 \ 0.1518 \ 0.0751 \ 0.3965]$  
$A_2 = [0.4408 \ 0.1374 \ 0.4218]$  
$A_3 = [0.2834 \ 0.7166]$  
$A_4 = [0.5689 \ 0.4311]$  
$A_5 = [0.8634 \ 0.1366]$  

Step 7. Calculate the first-level FSE results

Based on the first-level fuzzy weight vectors $A_i (i = 1, 2, \ldots, 5)$ and the membership matrixes $M_i (i = 1, 2, \ldots, 5)$, the first-level FSE can then be performed using equation (14):

$$B_1 = [0.0834 \ 0.6617 \ 0.2512 \ 0.0038]$$  
$$B_2 = [0.0334 \ 0.6126 \ 0.2694 \ 0.0846]$$  
$$B_3 = [0.0228 \ 0.5643 \ 0.3943 \ 0.0185]$$  
$$B_4 = [0.0814 \ 0.7129 \ 0.1914 \ 0.0143]$$  
$$B_5 = [0.7673 \ 0.1973 \ 0.0341 \ 0.0014]$$

Step 8. Calculate the second-level FSE

The first-level fuzzy evaluation results $B_i (i = 1, 2, \ldots, 5)$ constitute the following membership matrix $M$:

$$M = \begin{bmatrix} B_1 \\ \hline B_2 \\ \hline B_3 \\ \hline B_4 \\ \hline B_5 \end{bmatrix} = \begin{bmatrix} 0.0834 & 0.6617 & 0.2512 & 0.0038 \\ 0.0334 & 0.6126 & 0.2694 & 0.0846 \\ 0.0228 & 0.5643 & 0.3943 & 0.0185 \\ 0.0814 & 0.7129 & 0.1914 & 0.0143 \\ 0.7673 & 0.1973 & 0.0341 & 0.0014 \end{bmatrix}$$

To implement the second-level FSE, the second-level fuzzy weight vector $A$ must first be determined. We constructed the judgment matrix $D$ based on the 1 to 9 scaling method, and $D$ is then determined as follows:

$$D = \begin{bmatrix} 1 & 1 & 3 & 5 & 7 \\ 1 & 3 & 5 & 7 \\ 1/3 & 1/3 & 1 & 5 & 7 \\ 1/5 & 1/5 & 1/5 & 1 & 3 \\ 1/7 & 1/7 & 1/7 & 1/3 & 1 \end{bmatrix}$$

In addition, the weight vector $W$ and the maximum characteristic root $\lambda_{\text{max}}$ are:

$$W = [0.3567 \ 0.3567 \ 0.1845 \ 0.0667 \ 0.0353]^T$$

and

$$\lambda_{\text{max}} = 5.2677.$$  

The consistency index $CI$ is:

$$CI = 0.0669.$$  

The consistency ratio $CR$ is:

$$CR = 0.0597 < 0.1.$$
Obviously, the consistency ratio $CR$ shows a satisfactory consistency. Therefore, we can determine the second-level fuzzy weight vector as follows:

$$A = (W)^T = \begin{bmatrix} 0.3567 & 0.3567 & 0.1845 & 0.0667 & 0.0353 \end{bmatrix}$$

and thus

$$B = A \cdot M = \begin{bmatrix} 0.0784 & 0.6132 & 0.2724 & 0.0359 \end{bmatrix}$$

Each value of the synthetic evaluation model $B$ reflects the distribution status of the evaluation objects (CHWQ) specifically in terms of their properties (Good, Fine, Ordinary, Poor). According to the maximum membership principle of the FSE, $b_2 = 0.6132$ ($b_i \in B, i = 1, 2, 3, 4$), and we can conclude that the quality grade of the cable harness wiring for the phased array radar is “Fine”. Therefore, the results obtained using the single factor index of the FSE could not be regarded directly as the final quality grade; the determination of the CHWQ grade can only be determined by a single factor index-based comprehensive decision.

By applying the methods and steps described above to the remaining 49 sets of phased array radar wiring quality grade data in the FSE, we obtained 50 sets of quality grade FSE results for the phased array radar wiring (see Table 13).

The trained BP neural network is then used to predict the CHWQ for sets 51 to 60 of the phased array radar equipment. The predicted results are shown in Figure 9 and the corresponding predicted values are listed in Table 14.

From Table 14, we know that the CHWQ values of the 10 sets of phased array radar equipment declined gradually. Through research and analysis, we found that the main reason for this decline in the quality of the cable harness wiring was that the enterprise hired a group of new employees and the wiring of these 10 sets of phased array radar equipment was performed by these new employees. Because the new employees had no prior experience of cable harness wiring and were not skilled in cable harness assembly operations, these factors led to the reduction in the wiring quality. To address this phenomenon and thus improve the CHWQ, this batch of new staff must be trained systematically before wiring and on-site guidance should also be provided by an engineer with many years of installation experience in the actual wiring process.

![Comparison of the wiring effect before and after use of the method proposed in this paper.](image)

**Table 13. Fifty sets of quality grade FSE results for the phased array radar wiring.**

| Set no. | Quality grade | Set no. | Quality grade | Set no. | Quality grade | Set no. | Quality grade | Set no. | Quality grade |
|---------|---------------|---------|---------------|---------|---------------|---------|---------------|---------|---------------|
| 1       | 0.6132        | 11      | 0.7552        | 21      | 0.6209        | 31      | 0.6712        | 41      | 0.7689        |
| 2       | 0.5903        | 12      | 0.7736        | 22      | 0.5970        | 32      | 0.7068        | 42      | 0.7462        |
| 3       | 0.5497        | 13      | 0.7856        | 23      | 0.5763        | 33      | 0.7238        | 43      | 0.7243        |
| 4       | 0.5117        | 14      | 0.8014        | 24      | 0.5364        | 34      | 0.7642        | 44      | 0.7026        |
| 5       | 0.4939        | 15      | 0.8219        | 25      | 0.5198        | 35      | 0.7891        | 45      | 0.6847        |
| 6       | 0.5265        | 16      | 0.7754        | 26      | 0.5315        | 36      | 0.8050        | 46      | 0.6634        |
| 7       | 0.6032        | 17      | 0.7297        | 27      | 0.5524        | 37      | 0.8237        | 47      | 0.6510        |
| 8       | 0.6621        | 18      | 0.6766        | 28      | 0.5807        | 38      | 0.8509        | 48      | 0.6327        |
| 9       | 0.7008        | 19      | 0.6517        | 29      | 0.6056        | 39      | 0.8042        | 49      | 0.6108        |
| 10      | 0.7352        | 20      | 0.6397        | 30      | 0.6502        | 40      | 0.7854        | 50      | 0.6004        |

(Note: the above data were obtained based on the maximum membership principle).

FSE: fuzzy synthetic evaluation.

![Comparison of the wiring effect before and after use of the method proposed in this paper.](image)
Figure 8. Comparison chart of neural network output values and actual values.

Figure 9. Quality prediction chart of the FSE values. FSE: fuzzy synthetic evaluation.

Table 14. Values predicted by the BP neural network.

| Set no. | 51    | 52    | 53    | 54    | 55    | 56    | 57    | 58    | 59    | 60    |
|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Prediction values | 0.6176 | 0.6174 | 0.6168 | 0.6142 | 0.6032 | 0.5582 | 0.4204 | 0.2404 | 0.1616 | 0.1416 |

BP: back-propagation.
dotted line in Figure 8). This step is performed to obtain a neural network that can be used to make accurate predictions.

- In the prediction pattern, the network trained above is used to predict the FSE value of the CHWQ of 10 new phased array radar sets (see the 51st to 60th phased array radar sets shown in Figure 9).
- In Table 13, there are 50 sets of quality grade FSE results for phased array radar wiring. Among these sets, the value for the first set of 0.6132 is $b_2=0.6132$, which is solved using the method from Phase III in Figure 1. The remaining 49 sets of values (numbered 2–50) were also solved using the method from Phase III.
- Each FSE result corresponds to a quality grade for the cable harness wiring (Good, Fine, Ordinary, or Poor); for example, when $b_2=0.6132$, the corresponding quality grade is “Fine”.

**Quality control measures**

Cable harness wiring is a complex, time-consuming and costly process. In addition to the training of the workers and provision of on-site guidance, some quality control measures should also be adopted in the cable harness wiring process to ensure that each performance indicator meets the requirements of the target equipment. These related quality control measures are described as follows:

1. **Correct selection of the cable harness type.** Different cable harness types may have different diameters and use different material types. When different cable harness materials and types are used, the bending radius required during the wiring process will also be different. Therefore, when different types of cable harness are selected, different stiffness factors should be set in accordance with the requirements of the wiring environment.

2. **Classification of electrical performance.** Different types of wires, including power cables, signal cables, and control cables are installed in electronic equipment. The electromagnetic fields produced by the electricity around these cables will interfere with each other, and this will then affect the electrical performance of the machine. To prevent coupling crosstalk between the cable harnesses as far as possible, the designs of the cables and wires should be classified using bandings in accordance with the conductor signal’s current, voltage, frequency and other relevant properties.

3. **Standardization of routing of the cable harness.** To reduce coupling of the capacitance and the inductance, cable harness routing should be performed in straight lines and in alignment as far as possible. At the same time, the workers should also consider factors including the vibration resistance, heat dissipation, and ease of disassembly and maintenance. If rotating parts such as a revolving door or work stations are present, the transit cable harness should then be bent into a “U” shape.

4. **Correct sequence of installation.** The workers should perform the wiring operations in the following order: ① large diameter and corner cable harnesses should be wired first, and the small diameter and corner cable harnesses should then be installed; ② rigid cable
harnesses should be wired first, followed by the flexible cable harnesses; (2) high frequency harnesses should be wired first and then the low frequency harnesses should be wired; (3) high power harnesses should be wired first, followed by the low power harnesses.

(5) **Reasonable protection and fixing.** Cable harnesses have flexibility characteristics and are installed in large quantities; corresponding protection measures should be taken for wires that may be easily worn out or damaged. For example, a perforated liner or an insulation sleeve with a heat shrinkable casing could be installed. Fixed clamps and banding threads can also be used to fix the cable harness.

**Conclusions**

The structures of radar, satellite, aircraft, ships and other complex mechatronic products are becoming increasingly complex. Based on indicators of the main factors that influence the quality of cable harnesses, a quality prediction framework for cable harness wiring has been designed. The membership matrixes are established using extension theory. In addition, by combining the single factor and the synthetic fuzzy weight vector determined using the entropy weight method and the AHP, respectively, quality grade evaluation of the cable harness wiring is completed based on the FSE method. On the basis of the study described above, we used a BP neural network to realize quality prediction of the cable harness wiring for complex mechatronic products.

After studying the case above and discussing the related results, we would like to summarize three important aspects of the study as follows:

(1) The current cable harness wiring process is mainly reliant on the experience of the assembly workers and this makes it difficult to obtain guaranteed quality. In addition, the process still did not have an available set of perfect operations and a scientific evaluation method to address the aspects of CHWQ prediction and control. The case study results here show that one of the advantages of the method proposed in this paper is that it can provide more realistic predictions and decision-making results when compared with the traditional quality assurance methods.

(2) Reliance on the operator’s experience to ensure the quality of the cable harness wiring indicates the lack of a theoretical basis for the process. In this paper, the proposed method combined operational experience with theoretical knowledge (e.g. extension theory, the entropy weight method) and the results were then shown to be more credible.

(3) The factors that influence the quality of cable harness wiring have complex and changeable characteristics. These different factors have fuzzy characteristics and their importance is difficult to quantify. The application of extension theory and the FSE method in this paper solved these problems adequately. Therefore, the CHWQ prediction results are more accurate.

The next stage of this research work will be a study of cable harness fault diagnosis and performance degradation prediction of complex mechatronic products.

**Declaration of Conflicting Interests**

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**References**

1. Cerezuela C, Cauvin A, Boucher X, et al. A decision support system for a concurrent design of cable harnesses: Conceptual approach and implementation. *Concurrent Eng: Res Appl* 1998; 6: 43–52.

2. Park H, Cutkosky MR, Conru AB, et al. An agent-based approach to concurrent cable harness design. *AI EDAM* 1994; 8: 45–61.

3. Shang W, Liu J-H, Ning R-X, et al. A computational framework for cable layout design in complex products. In: 2012 international conference on medical physics and biomedical engineering (ed D Yang), Qingdao, China, 8–9 September 2012, Phys Procedia 2012, 33: 1879–1885.

4. Ning R, Liu J, Tang C, et al. Virtual assembly technology and its application. *Defense Manufacturing Technology* 2009; 4: 21–29.

5. Shang W, Ning R, Liu J, et al. Assembly process simulation for flexible cable harness in complex...
electromechanical products. Journal of Computer-Aided Design & Computer Graphics 2012; 24: 10.
6. Wang FL, Liao WH, Guo Y, et al. Research on cable harness information integrated model based on ontology for complex mechatronic products. In: 2013 27th Chinese control and decision conference. Qingdao, China, 23–25 May 2013, pp. 4167–4172. New York: IEEE.
7. Ng FM, Ritchie JM, Simmons J, et al. Designing cable harness assemblies in virtual environments. J Mater Process Technol 2000; 107: 37–43.
8. Ritchie JM, Robinson G, Day PN, et al. Cable harness design, assembly and installation planning using immersive virtual reality. Virtual Real 2007; 11: 261–273.
9. Conru AB. A genetic approach to the cable harness routing problem. In: First IEEE conference on evolutionary computation, IEEE world congress on computational intelligence, Orlando, FL, USA, 27–29 June 1994, pp. 200–205. New York: IEEE.
10. Van der Velden C, Bil C, Xinghuo Y, et al. An intelligent system for automatic layout routing in aerospace design. Innov Syst Softw Eng 2007; 3: 117–128.
11. Hermansson T, Bohlin R, Carlson JS, et al. Automated assembly path planning for wiring harness installations. J Manuf Syst 2013; 32: 417–422.
12. Mazzuchi TA, Linzey WG and Bruning A. A paired comparison experiment for gathering expert judgment for an aircraft wiring risk assessment. Reliab Eng Syst Safe 2008; 93: 722–731.
13. Tsai T-N. An adaptive diagnosis system for copper wire bonding process control and quality assessment in integrated circuit assembly. Int J Comp Integ M 2013; 26: 513–526.
14. Ertuğrul I and Güneş M. The usage of fuzzy quality control charts to evaluate product quality and an application. In: P Melin, O Castillo, EG Ramirez, J Kacprzyk and W Pedrycz (eds) Analysis and design of intelligent systems using soft computing techniques, Advances in soft computing, vol. 41. Berlin/Heidelberg: Springer, 2007, pp. 660–673.
15. Hou S-W and Tong S-R. Fuzzy number-based uncertain quality control chart and type selection. Comput Integr Manuf Syst 2012; 18: 415–421.
16. Yin C, Gan D-W, Liang Z-Q, et al. Evaluation and early warning method of key assembly process materials quality loss for complex electromechanical products. Comput Integr Manuf Syst 2014; 20: 1432–1442.
17. Cai W. Extension theory and its application. Chin Sci Bull 1999; 44: 1538–1548.
18. Guoqiang W, Wenwei Z and Jun Q. Research on comprehensive evaluation of regional power quality based on multistage extension method. In: Proceedings of 2011 Asia-Pacific power and energy engineering conference (APPEEC 2011), Wuhan, China, 25–28 March 2011, pp. 1–4. New York: IEEE.
19. Cai W and Shi Y. Extencis: its significance in science and prospects in application. J Harbin Inst Technol 2006; 38: 1079–1086.
20. Chunhua Z, Naiqi S, Tao W, et al. Study on danger evaluation of debris flow using extension method. In: 2012 international conference on systems and informatics (ICSAI 2012), Yantai, China, 19-20 May 2012, pp. 1352–1355. New York: IEEE.
21. Wong H and Hu BQ. Application of improved extension evaluation method to water quality evaluation. J Hydrol 2014; 509: 539–548.
22. Chen HC. Partial discharge identification system for high-voltage power transformers using fractal feature-based extension method. IET Sci Meas Technol 2013; 7: 77–84.
23. Lu RS, Lo SL and Hu JY. Analysis of reservoir water quality using fuzzy synthetic evaluation. Stoch Env Res Risk A 1999; 13: 327–336.
24. Cai W. The extension set and incompatibility problem. J Sci Explor 1983; 1: 81–93.
25. Wang MH, Chung YK and Sung WT. The fault diagnosis of analog circuits based on extension theory. In: Proceedings of 5th international conference on emerging intelligent computing technology and applications (ICIC 2009) (eds DS Huang, KH Jo, HH Lee, HJ Kang and V Bevilacqua), Lecture notes in computer science, vol. 5754. Berlin/Heidelberg: Springer, 2009, pp. 735–744.
26. Li L, Jianzhong Z, Xueli A, et al. Using fuzzy theory and information entropy for water quality assessment in Three Gorges region, China. Expert Syst Appl 2010; 37: 2517–2521.
27. Zhi-Hong Z, Yi Y and Jing-Nan S. Entropy method for determination of weight of evaluating indicators in fuzzy synthetic evaluation for water quality assessment. J Environ Sci 2006; 18: 1020–1023.
28. Groselj P and Stirn LZ. Acceptable consistency of aggregated comparison matrices in analytic hierarchy process. Eur J Oper Res 2012; 223: 417–420.
29. Saaty TL. Fundamentals of decision making and priority theory with the analytic hierarchy process, Analytic hierarchy process series, vol. 6. Pittsburgh: RWS Publications, 2000.
30. De Pina AC, De Pina AA, Albrecht CH, et al. ANN-based surrogate models for the analysis of mooring lines and risers. Appl Ocean Res 2013; 41: 76–86.
31. Kai-Li Z and Yao-Hong K. Neural network model and MATLAB simulation programming. Beijing: Tsinghua University Press, 2005.
32. Chen W, Tseng L and Wu C. A unified evolutionary training scheme for single and ensemble of feedforward neural network. Neurocomputing 2014; 143: 347–361.
33. Long J, Lan F, Chen J, et al. Mechanical properties prediction of the mechanical clinching joints based on genetic algorithm and BP neural network. Chin J Mech Eng 2009; 22: 36–41.
34. Dong X, Wang S, Sun R and Zhao S. Design of artificial neural networks using a genetic algorithm to predict saturates of vacuum gas oil. Pet Sci 2010; 7: 118–122.
35. Wang H and Liu M. Design of robotic visual servo control based on neural network and genetic algorithm. Int J Automat Comput 2012; 9: 24–29.
36. Ren T, Liu S, Yan G and Mu H. Temperature prediction of the molten salt collector tube using BP neural network. IET Renew Power Gener 2016; 10: 212–220.