Research on manufacturing process quality evaluation model and method of complex product based on IAHP

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Abstract. Manufacturing process quality is an important guarantee of complex product quality. More research is needed before we can provide an accurate evaluation of product quality. Analytic hierarchy process (AHP) was used to determine judgment matrix in many cases, but the results are not consistent with the real judgment process. In this paper, a comprehensive analysis based on improved analytic hierarchy process (IAHP) method is presented to solve the problem of multi-level quality evaluation in manufacturing process. Firstly, AHP method is used to build multi-level evaluation model of process quality for complex product. Then, a new three-demarcation matrix of IAHP is used to determine judgment matrix, a quantitative evaluation of influential factors on product assembly quality is realized. Finally, the major influential indicators of product quality can be gained by using the ordering results. The efficiency and scientifically of the approved method is verified by a practical example of ball valve product.

1. Introduction

With the development of manufacturing industry, the quality of industrial products plays an important role in promoting the progress of national economy. A product quality of manufacturing process is mainly determined through a series of processing and assembly processes to obtain product functionality and availability[1]. Firstly, the design process affects...
the overall product quality level through the correlation of manufacturing processes[2]. Moreover, the manufacturing process of mechanical and electrical products involves a variety of factors, including man, machine, material, method, measurement, environment and more than factors relating to each other. A variety of quality characteristics of product quality are interrelated and mutually influenced in the process of producing complex relationship, which might be referable for the design and manufacture process during complex, dynamic, sudden and accidental situations[3]. In addition, different quality characteristics are continuously transferred and finally formed the manufacturing process quality. It is made of various types of parts according to a certain manufacturing sequence, and circulated in a variety of processes under the interaction of multiple manufacturing process parameters. With the increasingly complicated and intelligent manufacturing process of products, the technical requirements which relying on the previous experience of quality management is far from enough to guarantee the product quality[4]. And the work activities of quality assurance technology guarantee the best product quality.

On the other hand, the control technology research on manufacturing process quality evaluation model and method received more and more praise from academic and industrial circles. Because of the inherent correlation between multiple factors affecting the quality of the manufacturing process, and the problems of incomplete data collection and insufficient data collection in enterprises, the single qualitative or quantitative method cannot be simply used for evaluation. By the analyses of manufacturing process quality, the relevance between processes and relevance between quality and factors have been confirmed[5]. The process quality and efficiency can be improved the quality by using optimized control technique[6]. With the introduction of manufacture techniques and quality control methods, a manufacturing process evaluation model and method was built to analyze quality change[7]. Based on the advanced quality control techniques, high quality products were produced by working together of working together of industry organization and quality managers[8].

In order to achieve the quantitative evaluation of the manufacturing process quality, the IAHP method of multilevel hierarchical structure was used in this paper. By implementing the quality evaluation and IAHP analysis of manufacturing process, the quality defects and quality fluctuations in manufacturing process can be found in time, which can reduce the rework cost and time. This paper is organized as follows. The quality evaluation model of ball valve is described in the next section. A quality evaluation of manufacturing process based on IAHP is presented in Section 3. And then, the approved method is illustrated by using an example of ball valve. Finally, some conclusions are pointed out in the final part.

2. Manufacturing process quality evaluation model and method

Ball valve is an important part of the equipment manufacturing industry. The main purpose of ball valve is to cut off or connect the medium in the pipeline and regulate and control the flow. Therefore, ball valve plays an important role in mechanical equipment industry in the key control part of fluid direction and pressure in pipeline fluid transportation system. In addition, ball valve manufacturing is a multi-process manufacturing process combining with lots of production technology courses. The manufacturing and quality control techniques were used to improve the highest level for ball valve based on the decision-making method of IAHP.
In order to accurately evaluate the quality of ball valve manufacturing process, it is necessary to establish a complete set of evaluation system. And influential indicators can be changed with the type of ball valve by using the dynamic adjustment. Through in-depth and meticulous investigation and analysis of the ball valve production line, the quality evaluation model of ball valve can be obtained based on the evaluation indicators of the existing literature. Taking a certain type of ball valve as an example, the influential indicators which influence the quality of ball valve manufacturing process are classified and sorted accordingly, and the process flow of ball valve manufacturing process is considered.

3. Quality evaluation process based on IAHP method

Analytic hierarchy process is a qualitative and quantitative decision analysis method, which is mainly used to analyze multi objective-decision making problems. AHP method needs to be divided into different related parts according to the nature of the problem and the goal of realization, and hierarchical model is also established according to the relationship[9]. Different from the classical AHP method, IAHP can more accurate and reasonable by using the construct of judgment matrix. So IAHP method can reduce the amount of calculation and improve the computational efficiency and accuracy of the method[10]. The standard of evaluation technology of IAHP method is one of the important standards to improve the ball valve quality in this paper. The steps of IAHP method are as follows:

(1) Building hierarchical structure model
According to the basic principle of analytic hierarchy process, the targets affecting targets are listed at a certain level.

(2) Establishing comparison matrix
The three-scale method is used to obtain the corresponding comparison matrix $S_{ij}$.

$$S_{ij} = \begin{bmatrix}
S_{i1} & S_{i2} & \cdots & S_{ir} \\
S_{i1} & S_{i2} & \cdots & S_{ir} \\
\vdots & \vdots & \ddots & \vdots \\
S_{in1} & S_{in2} & \cdots & S_{nin}
\end{bmatrix}$$

Where $S_{ij}$ represents the importance of the $i$-th factor versus the $j$-th factor.

$$S_{ij} = \begin{cases} 
2 & \text{(The factor } i \text{ is more important than the } j \text{ factor.)} \\
1 & \text{(The } i \text{ factor is as important as the } j \text{ factor.)} \\
0 & \text{(The factor } j \text{ is more important than the } i \text{ factor.)}
\end{cases}$$

(3) Calculating importance ranking index
The importance ranking index of $r_i$ was calculated in the following:

$$r_i = \sum_{j=1}^{n} S_{ij} \quad (i = 1, 2, \cdots, n)$$

The following setup steps assume that $r_{\text{max}} = \max\{r_i\}, r_{\text{min}} = \min\{r_i\}$.

(4) Constructing judgment matrix
By constructing the judgment matrix, its element $C_{ij}$ can be used in the following:

$$c_{ij} = \begin{cases} 
\frac{k_{m-1}}{r_{\text{max}}-r_{\text{min}}} (r_i - r_j) + 1 & (r_i \geq r_j) \\
\frac{k_{m-1}}{r_{\text{max}}-r_{\text{min}}} (r_j - r_i) + 1 & (r_i \leq r_j)
\end{cases}$$

(5) Calculating transfer matrix
The transfer matrix $P_{ij}$ of the construction judgment matrix $P_{ij}$ is calculated:

$$p_{ij} = \log c_{ij} \quad (i, j = 1, 2, \cdots, n)$$
(6) Obtaining optimal transfer matrix
The elements of optimal transfer matrix of $M_{ij}$ of the transfer matrix $P_{ij}$ were given as:

$$m_{ij} = \sum_{k=1}^{n} (c_{ik} - c_{jk}) / n \quad (6)$$

(7) Calculating judgment matrix
The quasi optimal matrix $S'$ of the judgement matrix $C_{ij}$ is calculated. Among them, the elements of the quasi optimal consistent matrix are:

$$m_{ij} = \log s'_{ij} \quad (7)$$

(8) Finding the eigenvectors
The eigenvector $\omega' = (\omega'_1, \omega'_2, \ldots, \omega'_n)^T$ can be normalized by using IAHP theory, and the specific weight of each element relative can be obtained in the following.

$$\omega = (\omega_1, \omega_2, \ldots, \omega_n)^T \quad (8)$$

(9) Calculating total weight
So the weight of the target layer for each index can be denoted as:

$$a \omega_i (i = 1, 2, \ldots, n) \quad (9)$$

4. An example
The framework of quality evaluation system was firstly presented in this paper. Then, a quality evaluation model was discussed through experiment study. In the case study, we investigate and analyze the ball valve quality requirements in manufacturing process, and summarize the relevant information of the process quality. The rationality and scientifically of IAHP method was verified with the machining process quality of valve cover of ball valve as an example. According to the quality requirements of machining process of ball valve cover, IAHP model of machining process quality of ball valve cover is established in Fig. 1.

![Machining accuracy of valve cover](image)

Figure 1. Analysis model of IAHP for machining accuracy of valve cover
According to IAHP analysis model of Fig. 1, the weights of each index which affects the machining accuracy of valve cover are calculated by using the five influencing indexes of processors. The calculation process based on IAHP is shown in the following.

Firstly, a comparison matrix was established according to Formula (1). Next, a judgment matrix was built by using Formulas (2) and (3).

$$S = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 \\
2 & 1 & 0 & 0 & 0 \\
2 & 2 & 1 & 2 & 2 \\
2 & 2 & 0 & 1 & 0 \\
2 & 2 & 0 & 2 & 1 \\
\end{bmatrix} \quad C = \begin{bmatrix}
1 & 1/3 & 1/9 & 1/5 & 1/7 \\
3 & 1 & 1/7 & 1/3 & 1/5 \\
9 & 7 & 1 & 5 & 3 \\
5 & 3 & 1/5 & 1 & 1/3 \\
7 & 5 & 1/3 & 3 & 1 \\
\end{bmatrix}$$

Then, the transfer matrix of judgment matrix was established according to Formula (4):
Next, the transfer matrix can be optimized according to Formula (5):

\[
P = \begin{bmatrix}
0.0000 & -0.4771 & -0.9542 & 0.6990 & -0.8451 \\
0.4771 & 0.0000 & 0.8451 & -0.4771 & -0.6990 \\
0.9542 & 0.8451 & 0.0000 & 0.6990 & 0.4771 \\
0.6990 & 0.4771 & -0.6990 & 0.0000 & -0.4771 \\
0.8451 & 0.6990 & -0.8451 & 0.4771 & 0.0000 \\
\end{bmatrix}
\]

Based on Formula (6), the quasi optimal consistent matrix was obtained as:

\[
S' = \begin{bmatrix}
1.0000 & 0.5173 & 0.0645 & 0.2540 & 0.1248 \\
1.9332 & 1.0000 & 0.1248 & 0.4911 & 0.2412 \\
15.4943 & 8.0149 & 1.0000 & 3.9363 & 1.9332 \\
3.9362 & 2.0362 & 0.2540 & 1.0000 & 0.4911 \\
8.0149 & 4.1406 & 0.5173 & 2.0362 & 1.0000 \\
\end{bmatrix}
\]

Finally, the eigenvector of the matrix \(S'\) was calculated as:

\[
\omega_{S1} = (0.2540, 0.4911, 3.9363, 1.0000, 2.0362)^T
\]

According to the theory of IAHP, the feature vectors were normalized to obtain the weight of each index which affects the assembly process.

\[
\omega_{S1} = \begin{pmatrix}
\omega_{S11} \\
\omega_{S12} \\
\omega_{S13} \\
\omega_{S14} \\
\omega_{S15}
\end{pmatrix}_T = (0.0329, 0.0636, 0.5100, 0.1296, 0.2638)_T
\]

Among them, \(\omega_{Sa_b}\) denotes the influence weight \(S_a\) of the criterion layer corresponding to the \(b\) index in the index layer, and \(\omega_{Za}\) denotes the influence weight of the criterion layer \(a\) to the target layer \(Z\). Similarly, it can be obtained as:

\[
\omega_{S2} = (0.5638, 0.1178, 0.0550, 0.2634)^T, \quad \omega_{S3} = (0.6923, 0.2308, 0.0769)^T
\]

\[
W_Z = (W_{Z1}, W_{Z2}, W_{Z3})^T = (0.6923, 0.2308, 0.0769)^T
\]

The weights of each index affecting assembly quality of ball valve are calculated:

\[
\omega_{D1} = \omega_{Z1}\omega_{S11} + \omega_{Z2}\omega_{S21} + \omega_{Z3}\omega_{S31} = 0.2061, \quad \omega_{D2} = \omega_{Z1}\omega_{S12} + \omega_{Z2}\omega_{S22} = 0.0712
\]

\[
\omega_{D3} = \omega_{Z1}\omega_{S13} + \omega_{Z2}\omega_{S23} + \omega_{Z3}\omega_{S33} = 0.3708, \quad \omega_{D4} = \omega_{Z1}\omega_{S14} + \omega_{Z2}\omega_{S24} = 0.1024
\]

\[
\omega_{D5} = \omega_{Z1}\omega_{S15} + \omega_{Z2}\omega_{S25} + \omega_{Z3}\omega_{S35} = 0.2493
\]

Finally, the weight of each target layer on the target layer is as follows:

\[
L = (D_1, D_2, D_3, D_4, D_5) = (\omega_{D1}, \omega_{D2}, \omega_{D3}, \omega_{D4}, \omega_{D5}) = (0.2016, 0.0712, 0.3708, 0.1024, 0.2493)
\]

Based on the above calculation results, the factors can be sorted as follows:

\[
D_3 > D_5 > D_1 > D_4 > D_2
\]

Based on the sorting results, it can be seen that the machining requirements of four through-hole positions of material is the main factors affecting machining quality of ball valve cover. In order to ensure the assembly technical objectives of subsequent assembly line, the quality of the manufacturing process of the ball valve can be ensured as a whole.

5. Conclusion
A detailed presentation of product quality evaluation and control techniques in manufacturing process were studied in this paper. The basic products properties and quality control for mechanical and electrical products was discussed in the case study. Based on the application of quality control technologies, the essentiality and feasibility was analyzed to improve product
quality. And the active technical specification of product quality and capability evaluation model was introduced in this paper. IAHP analysis method can consider as much information as possible through qualitative and quantitative, and it is simple and easy to achieve more rapid of computer automatic programming calculation in practice. It is reasonable and feasible to apply IAHP method to the analysis of factors affecting the quality of ball valve in manufacturing process. IAHP method can also provide a more reliable scientific basis for enterprises and customers to make decisions. The results indicated that IAHP method has important reference significance to improving product quality. A future study will investigate whether IAHP method is application of other mechanical and electrical products.

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