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An Improved Fuzzy Evaluation Method on Assimilability of Complex Product Design Scheme

Zefeng Zheng

Agricultural University of Hebei; Baoding, Hebei 071001, China
332443459@qq.com

Abstract

To effectively evaluate and analyze assimilability scheme of complex product, an improved evaluation method is proposed. It sets up three levels in the evaluation: scheme level, craft level and component level, giving evaluation indexes that can influence assimilability of complex product at every level. A corresponding evaluation index system is established. Based on the calculation of fuzzy distances and fuzzy nearness between different evaluation indexes, weighs of information entropy of indexes are gained. Then the levels of current complex product assembling scheme can be acquired. At last, specific project example is conducted to analyze and verify the model and the algorithm. The effectiveness and feasibility of the model and the algorithm are proven.

Keywords*: complex product; assimilability; fuzzy theory; information entropy; evaluation method*

1. Introduction

The evaluation on assimilability of product design scheme is not only a key design link of the Design For Assembly (DFA), but also one of the hotspot technologies focused on in the DFA research area [1-2]. The evaluation on product assimilability mainly measures the complexity of complicated systems in their component assembling processes. Potential problems in the subsequent machining and assembling processes need to be taken into consideration during the initial step of product design. Thus various limiting factors should be considered about during the assembling process. For complicated product and system, the formulation of assembling path and scheme involves a large number of components and parts. Therefore, reliable and functional evaluation of assemblabity of product design scheme is of great significance for the successful implementation of downstream product design. So far, some researches and discussions have been done by experts and scholars from different perspectives about DFA assimilability evaluation and corresponding models and algorithms have been proposed which are to some degree effective in the applications [7-11]. However, limitations still exist: 1), evaluation models are too simple not being able to reflect assimilability of product under certain situations; 2), evaluation magnitudes of fuzzy indexes are often made precise in evaluation analyses. So they are not exact fuzzy analyses. Credibility of results is therefore affected; 3), selections of assimilability evaluation in indexes are often one-sided. Models only study about components or assembly itself. They fail to evaluate from the perspectives of integrity and completeness. To solve these limitations, this paper proposes an improved fuzzy evaluation method for complex product assembling scheme.

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2. The Evaluation Index System of Assimilability of Complex Product Assembling Scheme

The selection of evaluation indexes of assimilability of complex product assembling scheme is based on the assembling features of the components and parts themselves and the features of generative process of assembling scheme. The former considers mainly about the effects characteristic parameters of components have on the assembling features. The latter focuses on the effects the assembling path and crafting have on the product assembling features from the perspective at scheme level.

2.1. The Evaluation Index of Assimilability at Component level

For components or assembly units, the evaluation of assimilability of product scheme needs to consider the following factor: 1), the quality of components; 2), the size of components; 3), the regularity of component structure; 4), the similarity of component structure; 5), the ability of being clamped of components; 6), the machining precision of components; 7), the standardization and interchangeability of components; 8), the maintainability of components.

The evaluation index system of assimilability at component level and specific content of each evaluation index are demonstrated below in Table 1.

Table 1. The Evaluation Index System of Assimilability at Component Level

	Evaluation index	Specific description
The evaluation index system of assimilability at component level	the quality of components c_1	The heavier the component is, the lower its assimilability is
	the size of components c_2	component's size being too large or small are both not good for assembly as the size being too large would increase the assembling space while being too small would make the assembly harder
	the regularity of component structure c_3	the more regular the component structure is, the better it is for the conjunction and the separation between components, and the better its assimilability is
	the similarity of component structure c_4	the higher the similarity of component structure is, the more consistent is the operative form of assembly, then the better is the assimilability
	the ability of being clamped of components c_5	the easier for components to be captured, clamped and positioned, the better is the assimilability
	the machining precision of components c_6	the higher the machining precision of components is, the higher the assembling requirement is and then the lower is the assimilability
	the standardization and interchangeability of components c_7	the more standardized is components and the higher of its quantity, the higher is the interchangeability and the better is the assimilability
	the maintainability of components c_8	the easier for components to be repaired, maintained and preserved, the better is the assimilability

2.2. The Evaluation Index of Assimilability at Scheme Level

From the perspective of integrity of product assembling scheme, the evaluation of assimilability of product scheme needs to consider the following factors: 1), the polymerizability of assembly; 2), the parallelism of assembly; 3), the accuracy of assembly; 4), the connect ability of assembly; 5), the path of assembly; 6), the compactness of structural scheme.

The evaluation index system of assimilability at scheme level and specific content of each evaluation index are demonstrated below in Table 2.

Table 2. The Evaluation Index System of Assimilability at Scheme Level

	Evaluation index	Specific description
The evaluation index system of assimilability at scheme level	the polymerizability of assembly c_9	the more the same or similar assembling operations are, the higher the polymerizability is, and the better is the assimilability
	the concurrency of assembly c_{10}	The more the assembling operations finished concurrently, the higher is the assembling efficiency and the better is the assimilability
	the accuracy of assembly c_{11}	The higher the assembly accuracy is or the stricter the requirements of cooperative relationship are, the lower is the assimilability
	the connect ability of assembly c_{12}	the more beneficial the assembling operations are for the conjunction and the fastening, the better is the assimilability
	the path of assembly c_{13}	The simpler the assembling path is and the less the re-direction and orientation operations are, the better is the assimilability
	the compactness of structural scheme c_{14}	under the conditions of guaranteeing assembling space, the more compact the structural scheme is, the shorter the assembling path would be, and then the better is the assimilability

3. The Evaluation Model of Assimilability of Complicated Product Assembling Scheme

3.1. The Confirmation of Comment Set

The evaluation indexes of assimilability of complicated product assembling scheme are generally fuzzy and uncertain. In order to conduct the evaluation reliably and effectively, this paper proposes an improved Carnahan J. V. method which uses “excellent”, “very good”, “good”, “fair”, “fairly poor”, “poor” and “very bad” as levels to evaluate the factors. The difference between this method and traditional ones is that the improved one tries to map the grading and fuzzy intervals in order to conduct effective quantitative measurement analysis. At the same time, considering that there are positive and negative indexes both, standardization and normalization need to be done to all indexes. Specific mapping relation is demonstrated in Table 3.

Table 3. The Grading and Fuzzy Mapping of Evaluation Indexes

Evaluation indexes	Levels of evaluation index						
	excellent g_7	Very good g_6	good g_5	fair g_4	Fair poor g_3	poor g_2	Very bad g_1
Positive index	Very large parameter value	Large parameter value	Preferably large parameter value	Fair parameter value	Fairly small parameter value	Small parameter value	Very small parameter value
Negative index	Very small parameter value	Small parameter value	Fairly small parameter value	Fair parameter value	Large parameter value	Preferably large parameter	Very large parameter value
Fuzzy intervals	0.9-1.0	0.8-0.9	0.7-0.8	0.6-0.7	0.5-0.6	0.4-0.5	0-0.4
Levels	7	6	5	4	3	2	1

3.2. The Fuzzy Distances and Fuzzy Nearness of Evaluation Levels

According to the principle of fuzzy membership, the closer evaluation indexes are from a evaluation level, the higher the degree of membership is and vice versa. Traditional methods try to confirm the degree of membership based on membership function. The size of the degree is often related to the adjacent evaluation level. The discrepancy between indexes and levels are then neglected. The method proposed by this paper measures the fuzzy membership function by measuring the fuzzy distances between evaluation levels after which the fuzzy nearness between levels is established.

If the evaluation index levels of assimilability of complicated product assembling scheme are L_S and L_T respectively, and $1 \le S \le 7$ $1 \le T \le 7$. The corresponding fuzzy intervals are $V(L_S) = [v^a_{L_S}, v^b_{L_S}]$ and $V(L_T) = [v^a_{L_T}, v^b_{L_T}]$ respectively. Then the fuzzy distance between L_S and L_T is $D(L_S, L_T)$:

$$D(L_S, L_T) = \sqrt[P]{\left|v^a_{L_S} - v^a_{L_T}\right|^P + \left|v^b_{L_S} - v^b_{L_T}\right|^P} / \sqrt[P]{2} \tag{1}$$

When $P = 1$, the fuzzy distance $D(L_S, L_T)$ is Hamming distance:

$$D(L_S, L_T) = \frac{\left|v^a_{L_S} - v^a_{L_T}\right| + \left|v^b_{L_S} - v^b_{L_T}\right|}{2} \tag{2}$$

When $P = 2$, then the fuzzy distance $D(L_S, L_T)$ is Euclidean distance:

$$D(L_S, L_T) = \frac{\sqrt{\left|v^a_{L_S} - v^a_{L_T}\right|^2 + \left|v^b_{L_S} - v^b_{L_T}\right|^2}}{\sqrt{2}} \tag{3}$$

Thus, the fuzzy nearness $\tau(L_S, L_T)$ between L_S and L_T is:

$$\tau(L_S, L_T) = 1 - D(L_S, L_T) \tag{4}$$

This paper adopts Euclidean distance to conduct analyses, consequently a chart of fuzzy nearness between different evaluations levels is generated which is shown in Table 4.

Table 4. The Fuzzy Nearness between Different Evaluation Levels

Evaluation levels	excellent	Very good	good	fair	Fair poor	poor	Very bad
excellent	1.000	0.900	0.800	0.700	0.600	0.500	0.235
Very good	0.900	1.000	0.900	0.800	0.700	0.600	0.333
Good	0.800	0.900	1.000	0.900	0.800	0.700	0.430
Fair	0.700	0.800	0.900	1.000	0.900	0.800	0.526
Fairly poor	0.600	0.700	0.800	0.900	1.000	0.900	0.619
Poor	0.500	0.600	0.700	0.800	0.900	1.000	0.708
Very bad	0.235	0.333	0.430	0.526	0.619	0.708	1.000

3.3. The Distribution of Information Entropy Weight of Evaluation Index

Different evaluation indexes of assimilability generally have different evaluation weights. On the basis of different evaluation index magnitudes, corresponding weights can be obtained by calculating entropy. If the evaluation magnitude of index j given by expert i is u_{ij}, then the original evaluation data matrix $\boldsymbol{U}_{ij}$

$$\boldsymbol{U}_{ij} = \begin{vmatrix} u_{11} & \cdots & u_{1j} & \cdots & u_{1n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ u_{i1} & \cdots & u_{ij} & \cdots & u_{in} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ u_{m1} & \cdots & u_{mj} & \cdots & u_{mn} \end{vmatrix} \tag{5}$$

The output entropy H_j of evaluation index j is:

$$H_j = -\frac{1}{\ln(m)} \sum_{k=1}^{m} \left(\frac{u_{ij}}{\sum_{i=1}^{m} u_{ij}} * \ln\left(\frac{u_{ij}}{\sum_{i=1}^{m} u_{ij}} \right) \right) \tag{6}$$

When $u_{ij} = 0$:

$$\ln\left(\frac{u_{ij}}{\sum_{i=1}^{m} u_{ij}} \right) = 0 \quad , 1 \le i \le m \; , 1 \le j \le n \tag{7}$$

The difference coefficient E_j of evaluation index of assimilability j can be indicated as:

$$E_j = 1 - H_j \, , 1 \le j \le n \tag{8}$$

Then the weight values w_j of evaluation indexes j based on the difference coefficient E_j are required as:

$$w_j = \frac{E_j}{\sum_{j=1}^{n} E_j} = \frac{1 - H_j}{n - \sum_{j=1}^{n} E_j}, \quad 1 \le j \le n \tag{9}$$

It can be seen from the equation that $0 \le w_j \le 1$ $\sum_{j=1}^{n} w_j = 1$.

3.4. The Evaluation Model and the Algorithm Implementation

Based on the discussion above, it can be concluded that the specific evaluation implementation steps of assimilability of complicated product scheme are:

Step1 Establish the generative index set of the evaluation index system of assimilability scheme, which is $C = (c_1, c_2, c_3, c_4, c_5, c_6, c_7, c_8, c_9, c_{10}, c_{11}, c_{12}, c_{13}, c_{14})$.

Step2 Establish the comment set $G = (g_1, g_2, g_3, g_4, g_5, g_6, g_7)$, and its corresponding scoring value is $V(G) = (1, 2, 3, 4, 5, 6, 7)$.

Step3 Experts evaluate in groups. Expert i 's comment about evaluation index j is used to calculate the fuzzy nearness τ_j based on Table 4. Then the evaluation magnitude u_{ij} of j from i is:

$$u_{ij} = \sum_{k=1}^{n=7} (g_k * \tau_j) \tag{10}$$

Step4 Adopt the calculation model of information entropy discussed in chapter 3.3, and then gains the weight w_j of different evaluation indexes.

Step5 to make the evaluation results more reliable, the fuzzy nearness τ_{jk} of evaluation index j which is commented by expert i needs to be calculated through Table 5. And the evaluation magnitude of j at the level of k is v_{jk} as:

$$v_{jk} = N_{jk} * \tau_{jk} \tag{11}$$

N_{jk} In the equation above is the number of experts who put the evaluation index j at the k level.

Then the evaluation matrix $\boldsymbol{B}(\boldsymbol{V})$ connecting evaluation indexes and evaluation levels is obtained as below:

$$\boldsymbol{B}(\boldsymbol{V}) = \begin{vmatrix} v_{11} & \cdots & u_{1k} & \cdots & u_{1N} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ u_{j1} & \cdots & u_{jk} & \cdots & u_{jN} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ u_{M1} & \cdots & u_{Mk} & \cdots & u_{MN} \end{vmatrix} \tag{12}$$

Step6 Considering that different evaluation indexes have different weights w_j, the sequence of evaluation values of assimilability of product design scheme is ψ :

$$\psi = W * \boldsymbol{B}(\boldsymbol{V}) = \left[w_1, \cdots, w_j, \cdots, w_M\right] \begin{vmatrix} u_{11} & \cdots & u_{1k} & \cdots & u_{1N} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ u_{j1} & \cdots & u_{jk} & \cdots & u_{jN} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ u_{M1} & \cdots & u_{Mk} & \cdots & u_{MN} \end{vmatrix} \tag{13}$$

Step7 According to the size of the values of different evaluation levels in the sequence, the virtues or defect degree of current assembling scheme is acquired following the evaluation principles below:

$$\psi_0 = \max(\psi_1, \cdots, \psi_k, \cdots, \psi_N) = \psi_t, \quad 1 \le k, t \le N \tag{14}$$

The evaluation level of t is the level of current assembling scheme.

Step8 the level of current assembling scheme tells whether this scheme meets assembling requirements or not, if yes, then the follow-up design links can be proceeded, if not, feedbacks need to be given and relevant design parameter values should be modified until they satisfy the requirements.

4. Example for Explanation and Analysis

Take the expert evaluation council of the assembly of a complicated product design scheme as an example to explain the implementation of the model and algorithm proposed. 13 Experts include equipment design experts, manufacturing experts, chief designers and department heads. Specific evaluation results are demonstrated in Table 5.

Table 5. The Expert Evaluation Results of Assimilability

Evaluation index	The number of evaluation experts						
	excellent	Very good	good	fair	Fairly poor	poor	Very bad
the quality of components c_1	0	9	4	0	0	0	0
the size of components c_2	0	2	8	3	0	0	0
the regularity of component structure c_3	0	2	6	5	0	0	0
the similarity of component structure c_4	0	1	3	7	2	0	0
the ability of being clamped of components c_5	4	7	2	0	0	0	0
the machining precision of	4	7	2	0	0	0	0

components c_6							
the standardization and interchangeability of components c_7	1	3	6	3	0	0	0
the maintainability of components c_8	0	6	4	2	1	0	0
the polymerizability of assembly c_9	1	3	6	3	0	0	0
the concurrency of assembly c_{10}	0	7	3	2	1	0	0
the accuracy of assembly c_{11}	3	6	2	2	0	0	0
the connect ability of assembly c_{12}	0	8	3	0	2	0	0
the path of assembly c_{13}	3	6	2	2	0	0	0
the compactness of structural scheme c_{14}	0	8	3	0	2	0	0

The original data matrix $\boldsymbol{U}_{13\times10}$ of evaluation indexes is then generated as:

$$\boldsymbol{U}_{13\times14}=\begin{vmatrix}
0.9 & 0.8 & 0.8 & 0.8 & 1.0 & 1.0 & 0.9 & 0.9 & 0.7 & 0.7 & 0.9 & 0.9 & 0.9 & 0.9 \\
0.9 & 0.8 & 0.7 & 0.7 & 0.9 & 1.0 & 0.8 & 0.8 & 0.8 & 0.6 & 1.0 & 0.9 & 0.9 & 0.9 \\
0.9 & 0.7 & 0.7 & 0.6 & 1.0 & 0.9 & 0.9 & 0.9 & 1.0 & 0.9 & 0.9 & 0.7 & 0.7 & \\
0.8 & 0.9 & 0.8 & 0.8 & 0.9 & 0.9 & 0.7 & 0.7 & 0.8 & 0.9 & 0.9 & 0.9 & 1.0 & 0.9 \\
0.9 & 0.8 & 0.9 & 0.7 & 0.9 & 1.0 & 0.8 & 0.9 & 0.9 & 0.8 & 0.9 & 0.5 & 0.8 & 0.9 \\
0.8 & 0.8 & 0.7 & 0.7 & 0.9 & 0.9 & 0.8 & 0.8 & 0.8 & 0.9 & 0.8 & 0.9 & 0.9 & 0.9 \\
0.9 & 0.9 & 0.8 & 0.9 & 1.0 & 0.9 & 0.8 & 0.9 & 0.7 & 0.7 & 0.7 & 0.5 & 0.7 & 0.6 \\
0.9 & 0.8 & 0.9 & 0.7 & 0.8 & 1.0 & 0.7 & 0.7 & 0.8 & 0.9 & 0.8 & 0.7 & 0.8 & 0.8 \\
0.8 & 0.8 & 0.8 & 0.6 & 0.9 & 0.8 & 1.0 & 0.9 & 0.9 & 0.8 & 0.9 & 0.9 & 1.0 & 0.9 \\
0.9 & 0.7 & 0.7 & 0.7 & 0.9 & 0.9 & 0.8 & 0.8 & 0.8 & 0.9 & 0.9 & 0.9 & 0.9 & 0.9 \\
0.9 & 0.8 & 0.8 & 0.8 & 0.9 & 0.9 & 0.7 & 0.8 & 0.8 & 0.8 & 1.0 & 0.9 & 0.9 & 0.8 \\
0.9 & 0.7 & 0.8 & 0.7 & 1.0 & 0.9 & 0.9 & 0.9 & 0.9 & 0.9 & 1.0 & 0.9 & 1.0 & 0.6 \\
0.8 & 0.8 & 0.7 & 0.7 & 0.8 & 0.8 & 0.8 & 0.6 & 0.7 & 0.9 & 0.7 & 0.7 & 0.9 & 0.9
\end{vmatrix}$$

Using the given evaluation index entropy weighing model, weights of each evaluation index are acquired and are listed in Table 6. Taking the fuzzy nearness of different evaluation indexes shown in Table 4 and effects different evaluation experts have on the indexes into account, the evaluation magnitudes of different evaluation indexes at each level are calculated as below in Table 6:

Table 6. The Weights and Evaluation Magnitudes of Assimilability Evaluation Indexes

Evaluation indexes	weight	Evaluation magnitudes						
		excellent	Very good	good	fair	Fairly poor	poor	Very bad
the quality of components c_1	0.074	0	8.1	3.2	0	0	0	0
the size of components c_2	0.069	0	1.8	6.4	2.1	0	0	0
the regularity of component structure c_3	0.067	0	1.8	4.8	3.5	0	0	0
the similarity of component structure c_4	0.061	0	0.9	2.4	4.9	1.2	0	0
the ability of being clamped of components c_5	0.078	4.0	6.3	1.6	0	0	0	0
the machining precision of components c_6	0.078	4.0	6.3	1.6	0	0	0	0
the standardization and interchangeability of components c_7	0.070	1.0	2.9	4.8	2.1	0	0	0
the maintainability of components c_8	0.070	0	5.4	3.2	1.4	0.6	0	0
the polymerizability of assembly c_9	0.070	1.0	2.7	4.8	2.1	0	0	0
the concurrency of assembly c_{10}	0.071	0	6.3	2.4	1.4	0.6	0	0
the accuracy of assembly c_{11}	0.075	3.0	5.4	1.6	1.4	0	0	0
the connect ability of assembly c_{12}	0.071	0	7.2	2.4	0	1.2	0	0
the path of assembly c_{13}	0.075	3.0	5.4	1.6	1.4	0	0	0
the compactness of structural scheme c_{14}	0.071	0	7.2	2.4	0	1.2	0	0

Since the weights of different evaluation indexes in the evaluating process are known, the sequence of evaluation values of assimilability of current product design scheme can be acquired as: $\psi = (1.214, 4.932, 3.043, 1.378, 0.332, 0, 0)$. After normalization processing, it is turned into $\overline{\psi} = (0.111, 0.453, 0.279, 0.126, 0.061, 0, 0)$. The sizes of different evaluation level values in the sequence tell that the level of current product assembling scheme is good.

5. Conclusion

This paper studied and analyzed the assimilability of complicated product assembling scheme and constructed a evaluation index system for the assimilability including the model and the method.

(1) The evaluation index systems at scheme level, craft level and component level are able to conduct analyses from the perspectives of integrity and completeness. Therefore the results are comprehensive and reasonable and also beneficial for advantageous modifications of assembling links.

(2) Considering that evaluation indexes are generally fuzzy and uncertain, the construction of fuzzy distances and fuzzy nearness of different evaluation indexes makes the evaluation process more effective. The model has clear physical significance. The calculation is fairly simple. To conclude, the model is of well practicability.

(3) The weights of evaluation indexes are acquired through information entropy and then are put in the evaluation model, making the evaluation results more objective and credible.

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