A Welding Unit Partition Method of Complex Weld Parts

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Abstract. Welding modularization can make the process planning and manufacturing of complex welding products easier, convenient and synergy. The appropriate units partition is critical for welding modularization. This paper proposes a method of welding units partition for complex welding parts. Firstly, the basic parts and sub parts of welding units are defined. Then, the basic parts are evaluated by using the fuzzy analytical hierarchy process (FAHP) method and the number of basic parts is determined by the improved units partition formula. Furthermore, the welding units are classified by the minimum spanning tree (MST) algorithm and the interference matrix is used to evaluate partition results. Finally, a rear sub frame of automobile is taken as an example to validate this method.

1. Introduction
Welding and mechanical assembly are the two most important processes to assemble the automobile as a whole. It is estimated that almost 50% of the production cost is due to the assembly planning costs [1]. As welding parameters such as welding sequence, welding time, impact the final quality of the automobile, various methods have been used by researchers to optimise welding sequence and to reduce welding time in the past study. The first research on welding sequences optimisation began in the 1940s [2]. With the development of artificial intelligence technology, different algorithms, such as neural network method [3], knowledge-based method [4], genetic algorithm [5], particle swarm optimisation algorithm, ant colony optimisation algorithm [6], have been used to solve the welding sequence optimisation problem with different fitness functions. However, these studies mainly aim to optimise robot spot welding sequence with fixed location. No previous study has addressed welding sequence optimisation for complex welding parts, which would be assembled at different work stations.

For complex welding parts with multiple welding processes, welding sequence planning is complex and time-consuming task. To improve welding sequence planning efficiency, an effective way is to divide the complex welding parts into several welding units. The unit partition as an effective method has always been applied in complex assembly planning. Liu Bo et al [7], used fuzzy clustering method to classify assembly units, which improves the intelligent level and efficiency of ship block assembly process design. Liu Ying [8], used the previous design results of assembly unit partition scheme to assist in the design of new assembly unit partition scheme. Appropriate units partition is critical for achieving collaborative design. However, the unit partition method used in complex welding parts has not been found in past studies.

Therefore, this paper proposes a method of welding unit partition for complex welding parts. FAHP is used as the calculation method of the basic parts, and the number of basic parts is determined by the
improved unit partition formula. Then the welding units are classified by the minimum spanning tree (MST) algorithm and the interference matrix is used to evaluate partition results. Finally, a rear sub frame of automobile is taken as an example to validate this method.

2. Definition of welding units
A welding assembly P needs n parts to be welded as a whole. Under certain constraints, P can be partitioned into n welding units \( U=\{u_1,u_2,\ldots,u_n\} \), and a welding unit includes a welding basic part and a certain number of welding sub parts. The structure of welding assembly is as shown in Figure 1.

![Figure 1](image)

**Figure 1.** The structure of welding assembly

The welding basic part is the centre connecting carrier of various welding sub parts, which should have the following features:

1) **Uniqueness:** One welding unit has and only one basic part, and can have no sub parts.

2) **Connectivity:** The base part is directly connected to sub parts in a welding unit.

3) **Convenience:** The basic part need withstand the welding deformation caused by the heat during welding. Therefore, the basic part is usually with the largest mass and volume in a welding unit.

4) **Similarity:** Symmetrical welding is used in the welding process, and similar structures can be welded at the same time to improve the quality of welding [9]. The similarity is calculated by the Euclidean Distance formula 1:

\[
S = \frac{(w_i - w_j)^2}{w_{\text{max}}} + \frac{(a_i - a_j)^2}{a_{\text{max}}} + \frac{(b_i - b_j)^2}{b_{\text{max}}}^{1/3}
\]  

(1)

Where \( w \) is the weight of welding part, \( a \) is the area of welding part, \( b \) is the centroid of welding part.

5) **Inclusion:** For a shell structure welded by a plurality of stamped metal sheets, if there is a support or a functional weld parts inside the shell, these parts should be partitioned into a welding unit.

3. Determination of basic parts
The analytic hierarchy process (AHP) is a multi-objective decision analysis method combining quantitative and qualitative analysis. However, this method has some problems, such as the difference between judgment consistency, difficulties in consistency testing and the lack of scientificity [10]. To solve the problem of consistency, the FAHP method is used to determine the basic parts, which uses the fuzzy complementary judgment matrix to evaluate the weights of parts. The steps of FAHP method are as follows:

**Step1:** Building the hierarchical structure model, shown in Figure 2.
Step2: According to the Table 1, the fuzzy judgment matrix A is obtained by comparing the target layer with the feature index layer.

### Table 1. Pair-wise comparison scale.

| Score | Comparison index       |
|-------|------------------------|
| 0.5   | Equal                  |
| 0.6   | Moderately preferred   |
| 0.7   | Strongly preferred     |
| 0.8   | Very strongly preferred|
| 0.9   | Extremely preferred    |
| 0.1, 0.2 | In contrast, if the judgment matrix of C\textsubscript{m} to C\textsubscript{n} is R\textsubscript{mn}, the judgment matrix of C\textsubscript{n} to C\textsubscript{m} is R\textsubscript{nm}=1-R\textsubscript{mn} |

Step3: The data of welding parts layer need to be normalized to the range of the fuzzy score before comparing the welding parts layer with the feature index layer. The normalization formula is as shown in equation 2.

\[
A_{ij} = \frac{P_i - P_j}{\max(P_i, P_j)} \times 0.4 + 0.5
\]  

Where \( P_i \) is ith welding parts; \( A_{ij} \) is fuzzy scale value of \( P_i \) versus \( P_j \).

Step4: The fuzzy complementary consistent matrix R can be obtained by transforming matrix A. The transformation formula is as shown in equation 3.

\[
R = \begin{bmatrix}
    r_{11} & r_{12} & \ldots & r_{1n} \\
    r_{21} & r_{22} & \ldots & r_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{n1} & r_{n2} & \ldots & r_{nn}
\end{bmatrix},
\]

\[
r_{ij} = \frac{r_i - r_j}{2(n-1)} + 0.5
\]  

Where \( r_i \) and \( r_j \) is the sum of the elements in ith and jth row of the matrix A respectively; \( r_{ij} \) is the element of the ith row and jth column in the matrix R; \( n \) is the order of the matrix R.

Step5: The weight values of elements in each layer can be calculated, as shown in equation 4.

\[
\alpha_i = \frac{1}{n} \cdot \frac{1}{2\alpha} + \frac{1}{n\alpha} \sum_{j=1}^{n} r_{ij}
\]  

Where \( \alpha \) is \((n-1)/2\).

4. Welding units partition and interference check method

4.1. Partition of welding units

Since the number of welding units and basic parts is the same, it is feasible to limit the number of assembly units. Ericsson et al [11] proposed the optimal unit number formula 5:

\[
1 < N_r \leq \sqrt{N}
\]  

Where \( N_r \) is the number of welding units; \( N \) is the number of welding parts.

Although formula 5 determines the range of unit number, it’s not suitable for the partition of welding units. It pays more attention to the heat deformation during welding, which will affect the quality of products. Thus, the formula is improved as shown in 6.

\[
1 < N_r \leq (N-N_k)^{0.2} + (N-N_k)^{0.5}
\]  

Where \( N_k \) is a special welding unit.

After determining the basic parts and the weights between the basic parts, the partition of the welding units is performed by the MST algorithm. It starts from the welding basic part to the sub parts.
4.2. Interference check

When any part is assembled in any direction of the coordinate system, the interference of the part with another part is represented in a matrix, which is called an interference matrix [12].

In the welding process, the welding unit is usually welded to another unit in six direction (±x, ±y, ±z). In the welding assembly U composed of n welding units, the orthogonal interference matrix of the welding units in the direction k (k=x, -x, y, -y, z, -z) is \( I_y \), as shown in equation 7.

\[
I_y = \begin{bmatrix}
I_{11y} & I_{12y} & \cdots & I_{1ny} \\
I_{21y} & I_{22y} & \cdots & I_{2ny} \\
\vdots & \vdots & \ddots & \vdots \\
I_{n1y} & I_{n2y} & \cdots & I_{nny}
\end{bmatrix}
\]

(7)

Where \( I_{ijy} \) is the interference between the ith part and the jth part when the ith part is assembled in the direction of y. The value of \( I_{ijy} \) is 0 (interference) or 1 (no interference).

When the welding unit \( U_1 \) moves in the +y direction, as shown in Figure 3(a), it interferes with \( U_2 \), \( I_{12y} = 0 \); when \( U_1 \) moves in the -z direction, it does not interfere with \( U_2 \), \( I_{21z} = 1 \). The interference matrix is shown in Figure 3(b).

(a) Interference instance explosion picture    (b) Interference matrix

**Figure 3.** Interference between two welding units

5. Case study

A rear sub frame of automobile shown in Figure 4 is taken as an example to verify the method.

5.1. Building a hierarchical model

As shown in Figure 4, the structure of rear sub frame is welded by large volume and mass parts. As \( P_{12} \) with large quality is welded in advance, if it is classified into a welding unit at the same time with \( P_{14} \), it is easy to make \( P_{14} \) produce large welding deformation. In this case, the indexes of connections need to be reduced. The relative weights of the basic parts in the rear sub frame are shown in Table 2.
The rear sub frame contains a special welding part $P_{12}$, $N_i=1$. According to formula 6 and the weight calculation of each part, as shown in Table 3, therefore, $P_{12}$, $P_5$, $P_4$, $P_6$, $P_3$, $P_{14}$ are basic parts. Then using MST method shown in Figure 5(a), which starts with the basic parts to sub parts based on the weight values shown in Table 3, welding units are determined as shown in Figure. 5(b). $U_1$ ($P_1$, $P_4$), $U_2$($P_2$, $P_3$, $P_{16}$), $U_3$($P_5$, $P_7$, $P_8$, $P_{10}$), $U_4$($P_6$, $P_9$, $P_{11}$), $U_5$($P_{13}$, $P_{14}$, $P_{15}$), $U_6$($P_{12}$). The rationality of partition result is further verified by interference check. According to a certain order $U_1\rightarrow U_3\rightarrow U_5\rightarrow U_4\rightarrow U_2\rightarrow U_6$, it is found that there is no interference, and the welding unit is classified reasonably.

Table 2. The fuzzy consistent judgment matrix and weights of the target layer.

|   | w   | v   | l   | e   | i   | s   | Weight |
|---|-----|-----|-----|-----|-----|-----|--------|
| w | 0.5 | 0.55| 0.6 | 0.9 | 0.6 | 0.85| 0.2067 |
| v | 0.45| 0.5 | 0.5 | 0.8 | 0.55| 0.7 | 0.1867 |
| l | 0.4 | 0.5 | 0.5 | 0.65| 0.5 | 0.75| 0.1787 |
| e | 0.1 | 0.2 | 0.35| 0.5 | 0.3 | 0.7 | 0.1327 |
| i | 0.4 | 0.45| 0.5 | 0.7 | 0.5 | 0.8 | 0.1806 |
| s | 0.15| 0.3 | 0.25| 0.3 | 0.2 | 0.5 | 0.1146 |

5.2. Units partition and interference check

The rear sub frame contains a special welding part $P_{12}$, $N_i=1$. According to formula 6 and the weight calculation of each part, as shown in Table 3, therefore, $P_{12}$, $P_5$, $P_4$, $P_6$, $P_3$, $P_{14}$ are basic parts. Then using MST method shown in Figure. 5(a), which starts with the basic parts to sub parts based on the weight values shown in Table 3, welding units are determined as shown in Figure. 5(b). $U_1$ ($P_1$, $P_4$), $U_2$($P_2$, $P_3$, $P_{16}$), $U_3$($P_5$, $P_7$, $P_8$, $P_{10}$), $U_4$($P_6$, $P_9$, $P_{11}$), $U_5$($P_{13}$, $P_{14}$, $P_{15}$), $U_6$($P_{12}$). The rationality of partition result is further verified by interference check. According to a certain order $U_1\rightarrow U_3\rightarrow U_5\rightarrow U_4\rightarrow U_2\rightarrow U_6$, it is found that there is no interference, and the welding unit is classified reasonably.

Table 3. The weights of basic parts.

| Part | Weight     | Part | Weight     | Part | Weight     | Part | Weight     |
|------|------------|------|------------|------|------------|------|------------|
| $P_1$| 0.05066224 | $P_3$| 0.07444707 | $P_9$| 0.06747178 | $P_{13}$| 0.04557972 |
| $P_2$| 0.05919667 | $P_6$| 0.07610272 | $P_{10}$| 0.04958779 | $P_{14}$| 0.07886231 |
| $P_3$| 0.0770381  | $P_7$| 0.05671893 | $P_{11}$| 0.07886231 | $P_{15}$| 0.05898788 |
| $P_4$| 0.07522823 | $P_8$| 0.06156757 | $P_{12}$| 0.06858044 | $P_{16}$| 0.04466278 |

6. Conclusion

A welding unit partition method is proposed in this paper, which can be applied to welding sequences planning to improve the efficiency of process planning. In order to verify the method, the rear sub frame of automobile is taken as an example. The results show that:

1) The method of determining basic parts by FAHP based on the features of the welding parts can solve the problem of consistency, and the units partitioned are more independent and convenient.
2) For the partition of basic parts with different welding structure features, the comparison between feature index layer and target layer is evaluated subjectively; the comparison between parts is evaluated objectively. It makes the method to be more applicable.

3) The result is determined by the improved unit partition formula and the interference matrix, and is verified to be feasible by the case study.

Acknowledgments
The authors would like to acknowledge the financial support from National Ministry of Industry and Information (Grant no. 2159999) and Key Science and Technology Program of Liuzhou (Grant no. 2018A0201e002).

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