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ORIGINAL ARTICLE

Modeling and application of mixed model assembly system complexity introduced by auto-body personalization

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Abstract Assembly system complexity, especially welding system complexity introduced by auto-body product personalization is regarded as a major contributor of uncertainty in the system planning and designing. The welding system complexity is defined based on information entropy theory, the station-level integrated complexity model, and system-level complexity flow model are established to obtain the complexity source of welding system. Complexity source sensitivity indices are proposed to indentify key station and key equipment that contribute most to the complexity. Based on the application of auto-body side welding line case, the result indicates that the proposed complexity model and key complexity source identifying and diagnosing process can be used as the decision support tool of auto-body welding system.

Keywords Information entropy · Complexity · Personalization · Welding system

1 Introduction

In the automotive industry, mixed model assembly line [1] is widely employed to deal with a variety of auto-body products, which allows the assembly of different variants of the common-based product on the same assembly line, and in the body plant, most assembly work is welding. This assembly line consists of many devices which are varying degrees of automation; besides, the configuration is complex. At the same time, the high number of auto-body product variety induced by personalization has significant negative impact on the mixed model assembly line. Therefore, it is necessary to study the information flow besides the material flow and the welding system complexity problems introduced by personalized factors.

Welding system is a complex system with a lot of equipments and operators. The complexity of welding system can be characterized in terms of its static structure or dynamic behavior. Static complexity, also termed as structural complexity, is concerned with the system's structure, configuration, the number and the variety of the products, and the system's variety of components. The dynamic complexity is related to the uncertainty of the system's behavior for a specific time period and deals with the probability of the system in control [2–4]. The more complex the system is, the greater the costs and potential failure of planning, design, and operation of the system will be. Therefore, it is necessary to study the complexity of manufacturing system, measure the complexity, and model the complexity of the system, especially in the welding system, in order to identify the sources of the complexity, and then, reduce and control the complexity.

In this paper, we propose models of station-level integrated complexity and system-level complexity including personalized subassembly information in the mixed model assembly line for personalized auto-body products. Then, we establish various sensitivity indices, indicating the contribution of complexity sources to the final evolutions, and put forward a process of identifying and diagnosing the complexity sources within the process planning. Based on the method above, we can access the key equipment and key station in which the complexity source is located. Then, we can pay more attention to these equipments and stations, and input a large amount of resources to reduce the complexity when we revise the process planning in a fast way. The remainder of this paper is structured as follows: in Section 1, measures and models of

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complexity for the production and manufacturing processes are reviewed; Sections 2 and 3, models for station-level integrated complexity and system-level complexity flow, respectively, are formulated; Section 4 analyzes the complexity source sensitivity of auto-body assembly line processes and system planning; in Section 5, a case study of the auto-body side welding line based on the mentioned model and method will be discussed; and finally, Section 6 summarizes the paper.

2 Background

In recent years, more and more researches have been taken on the complexity of manufacturing system. Complexity can be divided into two types depending on its domains, namely, the physical and the functional domains [4, 5]. In the functional domain, complexity is defined as a measure of uncertainty in achieving the functional requirements. This type of complexity is close to the manufacturing systems design and is further divided into time independent and time dependent. In the physical domain, manufacturing complexity is also further classified into two types, namely, static and dynamic. Due to the fluctuation of market demands, the manufacturing system must adapt to these changes; static or structural complexity and dynamic or operational complexity are increasing [6], especially in the condition of personalization. In fact, when it comes to assembly process, assembly cost, and product quality, complexity has occupied a certain position oriented to manufacturing process selection and optimal product design of assembly planning [7]. Although a unified precise definition of complexity has not made, there is a consensus that increased complexity has a negative effect on system performance [5, 8].

There are two approaches of analyzing a manufacturing system's complexity based on their theoretical origin. The first category is based on the methods and the concepts coming from the information theory [9–11], having as a fundamental measure, the Shannon entropy. The second category relies on the methods founded on axiomatic design theory [12]. Moreover, the chaos theory and the non-linear theory [4] are used to address complexity. So the information flow of auto-body welding system can be quantitatively analyzed by measuring the complexity in order to accurately understand and master the complex characteristics of the structure and operation of welding system.

In the condition of personalization, the number of varieties of products has increased dramatically. The auto-body product has a number of features which are product family, product platform, and modular, and as the number of its modules (function characteristics) are growing, the number of combinations are explosive. It also brings significant negative impact on the system performance including complicating assembly process, lowering productivity, and degrading quality, etc. [11]. So the complexity induced by variety brings many challenges to auto-body mixed model assembly line [11, 13, 14].

Garbie [15] discussed how to use the concepts of complexity to guide industrial enterprises analysts and designers with the most effective issues and perspective strategies for analyzing, planning, and eliminating complexity to satisfy the design of industrial enterprises. Vrabica and Butalaa [16] studied the complex of manufacturing organizations through the development of a metric for operational complexity. Samy and ElMaraghy [17] used that structure classification code in developing a metric for assessing the inherent structural complexity of manufacturing system, and they [18] also developed a mapping method between the complexity of product design and complexity of the corresponding assembly system. A domestic appliance drive assembly system [19] is used to demonstrate the use of the classification code to calculate the assembly system complexity. The developed complexity metrics [20, 21] can be used by designers as decision support tools to compare and rationalize various automated assembly systems alternatives and select the design that meets the requirements while reducing potential assembly complexity and associated cost. Zhang [22] developed a static entropy and a dynamic entropy of manufacturing systems based on the measurement and control of the states of manufacturing systems.

More specifically in the area of mixed-model assembly lines, Zhu et al. [23] defined a complexity measure in a mixed-model assembly line that incorporates both product variety and assembly process information based on Shannon's information entropy [9]. Wang et al. [24] proposed a product variety selection optimization method to find the best combination of product variety to be provided to the market, so that high market share can be achieved with low manufacturing complexity. However, these models are only limited to the serial assembly line. Wang and Hu [11] extended the complexity model to MAS with parallel and hybrid configurations. Wang et al. [25] extended the complexity model of Wang and Hu and developed a more general complexity model which allowed different variant produced at different parallel stations and developed methodologies of finding the optimal assembly sequences to minimize the system complexity.

However, researchers have made some researches on the definition and application of complexity in mixed model assembly line. But these researches still limit to the product varieties. They do not consider the welding line from a global perspective, neither do they introduce the auto-body product individual factors. In addition, they even do not identify and diagnose the complexity sources within the auto-body product mixed assembly system that may affect the system performance.

3 Station-level integrated complexity model

In the personalized auto-body welding line, manual stations coexist with automatic stations. It is a typical hybrid assembly mode. So in this section, the complexity induced by essential characteristics of station-level equipment and the complexity caused by the uncertainty presented to planners or operators when making choices of module variants are studied.

3.1 Station equipment complexity

Firstly, there is need to encode the equipment in auto-body assembly line, and equipment can be classified as: welding equipment, material handling equipment, and buffer device. After classification, welding equipment is encoded according to type, structure, control mode, and operation mode [19]. Similarly, material handling equipment and buffer device are encoded in the same way. Encoding operation defines the information content of every equipment in auto-body welding line and describes the static complexity of various equipment at station.

According to ElMaraghy et al. [20], the complexity of static structure is composed of three elements: total quantity of information, diversity of information, and the information content. At welding station, the complex degree of information which belongs to a certain particular devices of three kinds of equipments could be expressed by complexity index. The quantity and diversity of information can be comprehended by grasping the information content.

The complexity of welding equipment, material handling equipment, and buffer device at a specific station can be expressed as:

$$C_e = (n_e/N_e + I_e)[\log_2(N_e + 1)],\ e = M, MHS, B \quad (1)$$

Where M,MHS,B represent welding equipment, material handling equipment, and buffer device, respectively. n_e/N_e is the information diversity index, and n_e is the quantity of unique equipment of one kind at this station, N_e is the total quantity of equipment of one kind at this station, $\log_2(N_e+1)$ indicates the amount of information, and I_e is the overall average complexity index of equipment of one kind at this station indicates the information content.

As the consideration of station encoding, the station equipment complexity at station i can be written as the vector form:

$$C_i^E = \left[0, C_{\tilde{M}}^i, 0, 0\right]^T + \left[0, 0, C_{\tilde{MHS}}^i, 0\right]^T + \left[0, 0, 0, C_{\tilde{B}}^i\right]^T = \left[0, C_{\tilde{M}}^i, C_{\tilde{MHS}}^i, C_{\tilde{B}}^i\right]^T \quad (2)$$

In view of the importance of these three types of equipment in the welding line, equal weights are used during the calculation process, the coefficient of each element in the vector is 1.

3.2 Product subassembly selection complexity

In personalized auto-body product family, let A_k^S represent the set of modules to be assembled at station k. Each module r has V_r variants, the number of subassembly assembled by these modules is $N_k = \prod_{r \in A_k^S} V_r$. We define a vector $Q^{A_k^S} = \left[q_1^{A_k^S}, q_2^{A_k^S}, \dots, q_{N_k}^{A_k^S}\right]^T$, where $q_l^{A_k^S}$, l=1,2,…,N_k, is the demand proportion to each auto-body product variant.

Assume that the set of modules is assembled at serial station k, so there exist a number of N_k subassembly variants that station operators or planners need to select. At this time, the demand proportion of subassembly variant v_l is:

$$q_{kl} = q_l^{A_k^s}, l = 1, \dots, N_k \quad (3)$$

If the set of modules is assembled at parallel station, the total number of choice alternatives at station k is N_k, too. But due to the parallel separation of demand proportion of subassembly variant v_l, at this time, the probability of picking variant v_l is equal to:

$$q_{kl} = \frac{\theta_{kl} q_l^{A_k^s}}{\omega_k}, l = 1, \dots, N_k \quad (4)$$

Where θ_{kl} denotes the fraction that the subassembly variant v_l is assigned to the parallel station k, and let $\omega_k = \sum_{l=1}^{n_k} \theta_{kl} q_l^{A_k^s}$ be the product proportion of all subassembly variants assigned to the station k in the case of n_k parallel stations.

In this paper, we use the entropy function to define the complexity of station k as follows:

At serial welding station k,

$$H^1 = -\sum_{L=1}^{N_k} q_{kl} \log_2 q_{kl} \quad (5)$$

Where $q_{kl} = q_l^{A_k^s}$, l=1,…,N_k, Superscript 1 of the information entropy H^1 represents this station is serial welding station.

At parallel welding station k, and there are n_k parallel stations:

$$H^2 = -\sum_{l=1}^{N_k} \omega_k q_{kl} \log_2 \omega_k q_{kl} \quad (6)$$

Where Superscript 2 of the information entropy H^2 represents this station is parallel welding station.

Finally, at a specific welding station k, we can calculate the sum of the complexity according to the product variety at station and the complexity of welding equipment, material handling equipment, and buffer device as follows:

$$C_k^{In} = C_k^v + C_k^E = \left[C_k^v, 0, 0, 0\right]^T + C_k^E = [H^e, C_M, C_{MHS}, C_B] \quad (7)$$

where C_M,C_{MHS},C_B omit the station code, e=1, 2 represents series welding station and parallel welding station, respectively.

4 System-level complexity transformation model

4.1 Equivalent operation of hybrid structure of welding line

For the further analysis of complexity, the hybrid structure of welding line information flow needs to be equivalent simplified and removed all the included parallel structures in order to get complete serial structure. Figure 1 demonstrates the equivalent operation.

Firstly, equivalent series operation, □ operation, is used to simplify the serial stations in parallel section and then the serial configuration is treated as one station with the calculated complexity value. Equivalent parallel operation, ⊕ operation, is taken to simplify the parallel configuration which formed last step. Repeat this process until only one serial configuration remains [11].

4.2 System-level complexity flow model

Let A_i^s be the set of modules that are assembled at equivalent serial station $i(i=1,2,\ldots M)$. The number of subassembly variants (between the module and the final product) which are assembled from modules is $N_i = \prod_{r\in A_i^s} V_r$, so subassembly variants can be expressed as $v_i = \{v_{i1}, v_{i2}, \ldots, v_{iN_i}\}$, $l = 1,2,\ldots,N_i$. We define a vector $Q_i = \left[q_{i1}, q_{i1}, \ldots, q_{iN_i}\right]^T$, where $q_{il}, l=1,2,\ldots,N_i$ is the probability of the l subassembly being assembled at station i, and P is the final personalized auto-body product family.

We define a binary variable ξ_{il}^P, $l=1,2,\ldots,N_i$ to denote whether the personalized subassembly v_{il} assembled at station i is a part of personalized product family P, whether it will affect the equipment choice at station $i+1$.

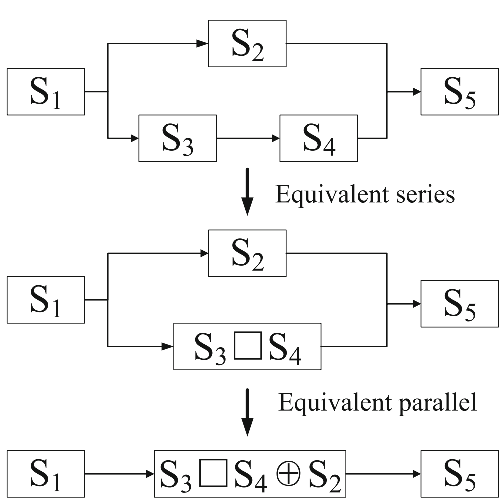

Fig. 1 Equivalent operation of hybrid structure

$$\xi_{il}^P = \begin{cases} 1 & \textit{personalized subassembly } v_{il} \textit{ assembled in station i is a part of personalized product family P} \\ 0 & \textit{otherwise} \end{cases}$$

According to the equipment classification in welding line, welding equipment, material handling equipment, and buffer device at the station are selected to do the welding operation, This choice behaviors are numbered 1(M), 2(MHS), and 3(B). To characterize the influence , for example, to establish the relationship between product variants at station i and equipment selection at station $i+1$, a relationship matrix between product variants and equipment selection is defined as follows:

$$\Phi_{i,i+1}^e = \begin{bmatrix} \phi_{1,1} & \phi_{2,1} & \cdots & \phi_{N_i,1} \\ \vdots & \vdots & \ddots & \vdots \\ \phi_{1,N_{i+1}^e} & \phi_{2,N_{i+1}^e} & \cdots & \phi_{N_i,N_{i+1}^e} \end{bmatrix} \tag{8}$$

where

$$\phi_{l,l'} = \begin{cases} 1 & \textit{subassembly } \text{varient } v_{il} \textit{ at station i requires equipment } (1,2,3) \textit{ selection at station } i+1 \textit{ to be in state } l' \\ 0 & \textit{otherwise} \end{cases}$$

When there are personalized modules, components assembled from these modules will be likely to result in change of equipment at downstream station. Therefore, it is necessary to study the effect of personalized subassembly to downstream station.

We define a vector $Q_i = \left[q_{i1}, q_{i1}, \ldots, q_{iN_i}\right]^T$, where q_{il}, $l=1,2,\ldots,N_i$ is the probability of the l th subassembly being assembled at station i, and by the definition of the vector $\zeta_i^P = \left[\zeta_{i1}^P, \zeta_{il}^P, \ldots, \zeta_{iN_i}^P\right]^T$, $l=1,2,\ldots,N_i$. The following relationship holds,

$$W_i = \left[\frac{\zeta_{i1}^P q_{i1}}{\sum_{l=1}^{N_i} \zeta_{il}^P q_{il}}, \frac{\zeta_{i2}^P q_{i2}}{\sum_{l=1}^{N_i} \zeta_{il}^P q_{il}}, \ldots, \frac{\zeta_{iN_i}^P q_{iN_i}}{\sum_{l=1}^{N_i} \zeta_{il}^P q_{il}}\right]^T = \frac{1}{Q_i^T \zeta_i^P} \zeta_i^P \cdot * Q_i \tag{9}$$

This equation indicates the demand vector of personalized subassembly variants at station i. Thus, the probability and the application of information entropy definition, the complexity induced by personalized components at station i,are defined as:

$$H_{W_i}^1 = H(W_i) = -\sum_{l=1}^{N_i} \frac{\zeta_{il}^P q_{il}}{\omega_i} \cdot \log_2 \frac{\zeta_{il}^P q_{il}}{\omega_i} \tag{10}$$

Where $\omega_i = Q_i^T \zeta_i^P = \sum_{l=1}^{N_i} \zeta_{il}^P q_{il}$, $H_{W_i}^1$ is the complexity, Superscript 1 indicates that this station is defined as a serial station. W operator represents the introduction of individualized factors, and the personalized components resulting complexity is obtained through calculating the information entropy value of component vector on the station.

When personalized subassembly assembled at station i, the probability of the equipment at station $i+1$, being in an alternative state, is q_f^e, $f=1,2,\ldots,N_{i+1}^1$. Now, the information entropy calculated by these probabilities is:

$$H\left(Q_{i,i+1}^e\right)=-\sum_{l'}^{N_{i+1}^e} q_{l'}^e\cdot\log_2 q_{l'}^e \tag{11}$$

This equation indicates the uncertainty of equipment selection at next station caused by the personalized components assemble at last station, the transmission equipment selection complexity. Also define as:

$$\Phi_{i,i+1}^e\left(H_{W_i}^1\right)=H\left(Q_{i,i+1}^e\right) \tag{12}$$

Where $e\in\{1,2,3\}$ and 1=M, 2=MHS, and 3=B. Here, $\Phi_{i,i+1}^e$ is also regarded as operator and it can also be considered as the form of conversion functions; it considers the complexity caused by personalized subassembly at station i and calculates the information entropy of equipment selection at station $i+1$, to acquire the personalized component induced equipment selection complexity. $\Phi_{i,i+1}^e(W(H_i^1))=\Phi_{i,i+1}^e\cdot W(H_i^1)=H(Q_{i,i+1}^e)$, where $\Phi_{i,i+1}^e\cdot W$ indicate the complex relationship of transition function and H_i^1 is the subassembly variants complexity at serial station i.

According to the state space theory, the complexity flow model is established:

$$\begin{bmatrix} C_{i+1}^v \\ C_M^{i+1} \\ C_{MHS}^{i+1} \\ C_B^{i+1} \end{bmatrix}=\begin{bmatrix} 0 & 0 & 0 & 0 \\ \Phi_{i,i+1}^1\cdot W\left(H_i^1\right)/H_i^1 & 0 & 0 & 0 \\ \Phi_{i,i+1}^2\cdot W\left(H_i^1\right)/H_i^1 & 0 & 0 & 0 \\ \Phi_{i,i+1}^3\cdot W\left(H_i^1\right)/H_i^1 & 0 & 0 & 0 \end{bmatrix}\times\begin{bmatrix} C_i^v \\ C_M^i \\ C_{MHS}^i \\ C_B^i \end{bmatrix}+\begin{bmatrix} H_{i+1}^1 \\ 0 \\ 0 \\ 0 \end{bmatrix}+\begin{bmatrix} 0 \\ C_{\tilde{M}}^{i+1} \\ 0 \\ 0 \end{bmatrix}+\begin{bmatrix} 0 \\ 0 \\ C_{M\tilde{H}S}^{i+1} \\ 0 \end{bmatrix}+\begin{bmatrix} 0 \\ 0 \\ 0 \\ C_{\tilde{B}}^{i+1} \end{bmatrix}$$

Because $\mathbf{C}_i^v=[C_i^v,0,0,0]^T=[H_i^1,0,0,0]^T$, so there is:

$$\begin{bmatrix} C_i^v \\ C_M^i \\ C_{MHS}^i \\ C_B^i \end{bmatrix}=\begin{bmatrix} 0 & 0 & 0 & 0 \\ \Phi_{i-1,i}^1\cdot W\left(C_{i-1}^v\right)/C_{i-1}^v & 0 & 0 & 0 \\ \Phi_{i-1,i}^2\cdot W\left(C_{i-1}^v\right)/C_{i-1}^v & 0 & 0 & 0 \\ \Phi_{i-1,i}^3\cdot W\left(C_{i-1}^v\right)/C_{i-1}^v & 0 & 0 & 0 \end{bmatrix}\times\begin{bmatrix} C_{i-1}^v \\ C_M^{i-1} \\ C_{MHS}^{i-1} \\ C_B^{i-1} \end{bmatrix}+\begin{bmatrix} H_i^1 \\ 0 \\ 0 \\ 0 \end{bmatrix}+\begin{bmatrix} 0 \\ C_{\tilde{M}}^i \\ 0 \\ 0 \end{bmatrix}+\begin{bmatrix} 0 \\ 0 \\ C_{M\tilde{H}S}^i \\ 0 \end{bmatrix}+\begin{bmatrix} 0 \\ 0 \\ 0 \\ C_{\tilde{B}}^i \end{bmatrix} \tag{13}$$

Where $i=1,2,\ldots,n$ are n serial welding stations after equivalent operation, $C_0^v=H_0^1$, is the complexity of the base subassembly, $C_M^0=0, C_{MHS}^0=0, C_B^0=0$.

$$\boldsymbol{C}_i=\boldsymbol{A}_{i-1}\boldsymbol{C}_{i-1}+\boldsymbol{C}_i^v+\boldsymbol{u}_i^1+\boldsymbol{u}_i^2+\boldsymbol{u}_i^3=\boldsymbol{A}_{i-1}\boldsymbol{C}_{i-1}+\boldsymbol{C}_i^{In}, i=1,2,\ldots,M$$
$$\boldsymbol{y}_i=\ \boldsymbol{D}_i\boldsymbol{C}_i,\quad \{i\}\subset\{1,2,\ldots,M\}$$

So $\boldsymbol{y}_i$ can also express as follows:

$$\begin{aligned}\boldsymbol{y}_i &=\sum_{h=1}^{i}\boldsymbol{D}_i\boldsymbol{\Psi}_{i,h}\boldsymbol{C}_h^{In}+\boldsymbol{D}_i\boldsymbol{\Psi}_{i,0}\boldsymbol{C}_0\\ &=\sum_{h=1}^{i}\boldsymbol{D}_i\boldsymbol{\Psi}_{i,h}\boldsymbol{C}_h^v+\sum_{h=1}^{i}\boldsymbol{D}_i\boldsymbol{\Psi}_{i,h}\boldsymbol{u}_h^1+\sum_{h=1}^{i}\boldsymbol{D}_i\boldsymbol{\Psi}_{i,h}\boldsymbol{u}_h^2\\ &\quad+\sum_{h=1}^{i}\boldsymbol{D}_i\boldsymbol{\Psi}_{i,h}\boldsymbol{u}_h^3+\boldsymbol{D}_i\boldsymbol{\Psi}_{i,0}\boldsymbol{C}_0\end{aligned} \tag{14}$$

where $\boldsymbol{\Psi}_{i,h}=A_{i-1}A_{i-2}\ldots A_h$ is the state transition matrix and $\boldsymbol{y}_i$ is the expert assessment of the key product characteristics of subassembly at station i through testing and measuring. At the end of welding line, the expert assessment of final personalized auto-body product family is conducted. When $i=M$,

$$\begin{aligned}\boldsymbol{y}_M=\boldsymbol{D}_M\boldsymbol{C}_M &=\sum_{i=1}^{M}\boldsymbol{D}_M\boldsymbol{\Psi}_{M,i}\boldsymbol{C}_i^{In}+\boldsymbol{D}_M\boldsymbol{\Psi}_{M,0}\boldsymbol{C}_0\\ &=\sum_{i=1}^{M}\boldsymbol{D}_M\boldsymbol{\Psi}_{M,i}\boldsymbol{C}_i^v+\sum_{i=1}^{M}\boldsymbol{D}_M\boldsymbol{\Psi}_{M,i}\boldsymbol{u}_i^1\\ &\quad+\sum_{i=1}^{M}\boldsymbol{D}_M\boldsymbol{\Psi}_{M,i}\boldsymbol{u}_i^2+\sum_{i=1}^{M}\boldsymbol{D}_M\boldsymbol{\Psi}_{M,i}\boldsymbol{u}_i^3+\boldsymbol{D}_M\boldsymbol{\Psi}_{M,0}\boldsymbol{C}_0\\ &=\boldsymbol{\Gamma}_M\boldsymbol{C}_M^c+\boldsymbol{\Gamma}_M\boldsymbol{U}_M^1+\boldsymbol{\Gamma}_M\boldsymbol{U}_M^2+\boldsymbol{\Gamma}_M\boldsymbol{U}_M^3+\boldsymbol{\Gamma}_0\boldsymbol{C}_0\end{aligned} \tag{15}$$

where $\boldsymbol{\Gamma}_M=[[\boldsymbol{D}_M\boldsymbol{\Psi}_{M,1}][\boldsymbol{D}_M\boldsymbol{\Psi}_{M,2}]\cdots[\boldsymbol{D}_M\boldsymbol{\Psi}_{M,M}]]$, $\boldsymbol{\Gamma}_0=\boldsymbol{D}_M\boldsymbol{\Psi}_{M,0}$, $\boldsymbol{C}_M^c=[(\boldsymbol{C}_1^v)^{\mathrm{T}},\ldots,(\boldsymbol{C}_M^v)^{\mathrm{T}}]^{\mathrm{T}}$, $\boldsymbol{U}_M^1=[(\boldsymbol{u}_1^1)^T,\ldots,(\boldsymbol{u}_M^1)^T]^T$, $\boldsymbol{U}_M^2=[(\boldsymbol{u}_1^2)^T,\ldots,(\boldsymbol{u}_M^2)^T]^T$, and $\boldsymbol{U}_M^3=[(\boldsymbol{u}_1^3)^T,\ldots,(\boldsymbol{u}_M^3)^T]^T$.

$$\boldsymbol{Y}=\begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_M \end{bmatrix}=\boldsymbol{\Gamma}\begin{bmatrix} C_1^v \\ C_2^v \\ \vdots \\ C_M^v \end{bmatrix}+\boldsymbol{\Gamma}\begin{bmatrix} u_1^1 \\ u_2^1 \\ \vdots \\ u_M^1 \end{bmatrix}+\boldsymbol{\Gamma}\begin{bmatrix} u_1^2 \\ u_2^2 \\ \vdots \\ u_M^2 \end{bmatrix}+\boldsymbol{\Gamma}\begin{bmatrix} u_1^3 \\ u_2^3 \\ \vdots \\ u_M^3 \end{bmatrix} \tag{16}$$

wherein,

$$\boldsymbol{\Gamma}=\begin{bmatrix} \boldsymbol{D}_1 & 0 & \cdots & 0 \\ \boldsymbol{D}_2\boldsymbol{\Psi}_{2,1} & \boldsymbol{D}_2 & \cdots & \\ \vdots & \vdots & \ddots & \vdots \\ \boldsymbol{D}_M\boldsymbol{\Psi}_{M,1} & \boldsymbol{D}_M\boldsymbol{\Psi}_{M,2} & \cdots & \boldsymbol{D}_M \end{bmatrix}$$

The essence of complexity flow model is to obtain the mathematical relationship between welding line complexity source and the auto-body key product characteristics. $\boldsymbol{y}_M=D_MC_M$ indicates the expert evaluation of final auto-body product family quality. Due to the product family quality is controlled by a set of process factors, and these process factors are determined primarily by the selection of process equipment on the auto-body welding line. Therefore, analyzing the complexity introduced by process equipment and auto-body product personalized subassembly complexity introduced by designing is one of the methods that can evaluate the performance of welding line process and system planning.

5 Complexity source sensitivity analysis in the process and system planning of auto-body welding line

Based on the system level complexity flow model, sensitivity analysis is used to assess the influence of every complexity source to the quality of personalized auto-body product family; This can be used as a decision support tool that guides the revision and improves the process and system planning. The steps of sensitivity analysis can be summarized as follows:

Step 1: The equipment sensitivity index (the impact of equipment selection uncertainty to the quality of auto-body product family) is compared with the subassembly variants sensitivity index (the influence of subassembly variants uncertainty to the quality of auto-body product family) to determine the main complexity source in the process planning.

Step 2: If the main complexity source is caused by equipment, then we should compare sensitivity indices of equipment to every product quality key feature with the equipment sensitivity index, calculated in Step 1, to determine the key characteristic of key product. If the main complexity source is caused by subassembly variants, then we should compare sensitivity indices of subassembly variants to every product quality key feature with the subassembly variants sensitivity index, calculated in Step 1, to determine the key characteristic of key product.

Step 3: Determine the key complexity source and the key station in which the complexity source lies, then revise the key station and key complexity source in order to improve the process and system planning and to enhance its robustness.

Assume the welding line, which includes M stations. There are subassembly variants complexity, welding equipment complexity, material handling equipment complexity, and buffer device complexity in every station. The final product of welding line is personalized auto-body product family, which has I key product features. Some sensitivity indices can be calculated as follows:

(1) Welding equipment sensitivity index in Station k

This index represents the effect of welding equipment to the single product key feature or the product family, which is as follows. Firstly, to the automobile body product key characteristic:

$$\Sigma S^{y_i}_{U^1_{j,k}} = abs\left(\frac{\partial \boldsymbol{y}_i}{\partial \boldsymbol{U}^1_{j,k}} \frac{\Delta \boldsymbol{U}^1_{j,k}}{\Delta \boldsymbol{y}_i}\right) = abs\left(\boldsymbol{\Gamma}_{i,j} \frac{\Delta \boldsymbol{U}^1_{j,k}}{\Delta \boldsymbol{y}_i}\right) \tag{17}$$

Wherein, $\boldsymbol{\Gamma}_{i,j}$ is the element in row i and column j element in the matrix $\boldsymbol{\Gamma}_M$, $\Delta \boldsymbol{U}^1_{j,k}$ and $\Delta \boldsymbol{y}_i$ are the tolerance of welding equipment complexity source, and the tolerance of product key characteristic $\boldsymbol{y}_i$ in Station k, respectively. This function indicates the influence of welding equipment j to product key characteristic $\boldsymbol{y}_i$. To the product family:

$$S^{\boldsymbol{Y}}_{\boldsymbol{U}^1_{j,k}} = \frac{1}{I} \sum_{i=1}^{I} S^{\boldsymbol{y}_i}_{\boldsymbol{U}^1_{j,k}} \tag{18}$$

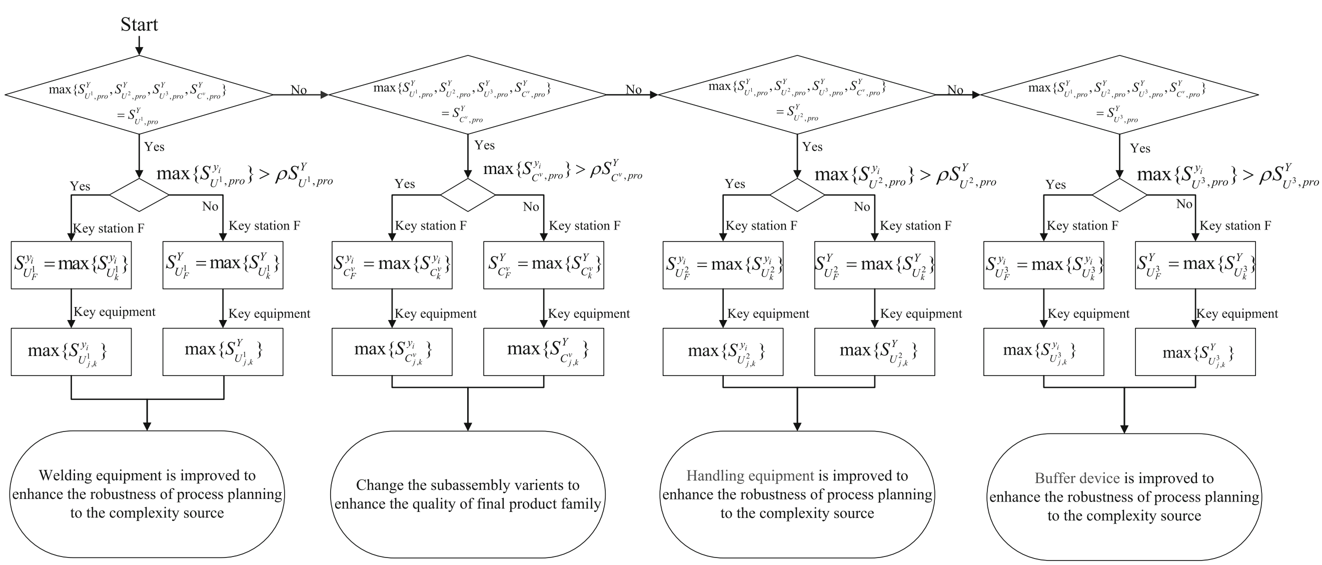

Fig. 2 Key complexity source identifying and diagnosing process. (Note: max $\left\{S^Y_{U^1,pro}, S^Y_{U^2,pro}, S^Y_{U^3,pro}, S^Y_{C^v,pro}\right\}$)

Wherein, $S^{\boldsymbol{Y}}_{\boldsymbol{U}^1_{j,k}}$ is the mean influence of welding equipment j to product family key characteristic. So the influence of welding equipment to product key characteristic $\boldsymbol{y}_i$ in this station is:

$$S^{\boldsymbol{y}_i}_{\boldsymbol{U}^1_k} = \frac{1}{N_{U^1_k}} \sum_{j=1}^{N_{U^1_k}} S^{\boldsymbol{y}_i}_{U^1_{j,k}} \tag{19}$$

Where $N_{\boldsymbol{U}^1_k}$ is the welding equipment coding number in Station k. The mean influence to product family key characteristic is:

$$S^{\boldsymbol{Y}}_{\boldsymbol{U}^1_k} = \frac{1}{I} \sum_{i=1}^{I} S^{\boldsymbol{y}_i}_{\boldsymbol{U}^1_k} \tag{20}$$

(2) Accordingly, the material handling equipment sensitivity indices and the buffer device sensitivity indices are:

$$\begin{aligned} S^{\boldsymbol{y}_i}_{\boldsymbol{U}^2_k} &= \frac{1}{N_{U^2_k}} \sum_{j=1}^{N_{U^2_k}} S^{\boldsymbol{y}_i}_{U^2_{j,k}} \quad & S^{\boldsymbol{y}_i}_{\boldsymbol{U}^3_k} &= \frac{1}{N_{U^3_k}} \sum_{j=1}^{N_{U^3_k}} S^{\boldsymbol{y}_i}_{U^3_{j,k}} \\ S^{\boldsymbol{Y}}_{\boldsymbol{U}^2_k} &= \frac{1}{I} \sum_{i=1}^{I} S^{\boldsymbol{y}_i}_{\boldsymbol{U}^2_k} \quad & S^{\boldsymbol{Y}}_{\boldsymbol{U}^3_k} &= \frac{1}{I} \sum_{i=1}^{I} S^{\boldsymbol{y}_i}_{\boldsymbol{U}^3_k} \end{aligned} \tag{21}$$

(3) The effect of subassembly variants, causing complexity to the final product in station k, can also acquire a series of sensitivity indices through the above method:

$$\Sigma S^{\boldsymbol{y}_i}_{C^v_{j,k}} = abs\left(\frac{\partial \boldsymbol{y}_i}{\partial \boldsymbol{C}^v_{j,k}} \frac{\Delta \boldsymbol{C}^v_{j,k}}{\Delta \boldsymbol{y}_i}\right) = abs\left(\boldsymbol{\Gamma}_{i,j} \frac{\Delta \boldsymbol{C}^v_{j,k}}{\Delta \boldsymbol{y}_i}\right) \tag{22}$$

$$\begin{aligned} S^{\boldsymbol{y}_i}_{\boldsymbol{C}^v_k} &= \frac{1}{N_k} \sum_{j=1}^{N_k} S^{\boldsymbol{y}_i}_{\boldsymbol{C}^v_{j,k}} \\ S^{\boldsymbol{Y}}_{\boldsymbol{C}^v_k} &= \frac{1}{I} \sum_{i=1}^{I} S^{\boldsymbol{y}_i}_{\boldsymbol{C}^v_k} \end{aligned} \tag{23}$$

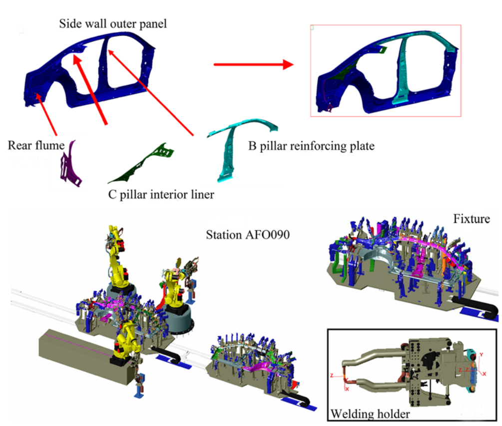

Fig. 3 Automatic positioned welding station

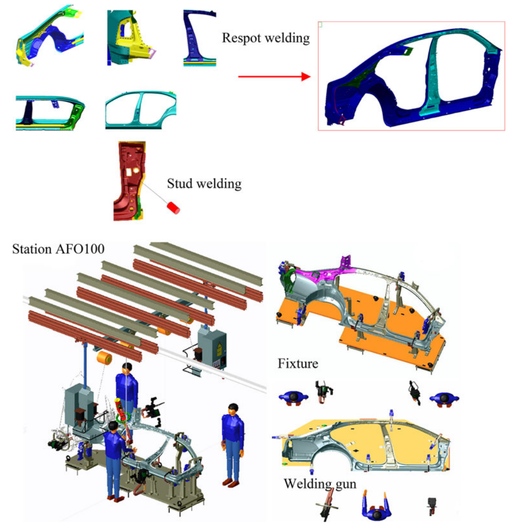

Fig. 4 Respot welding/stud welding station

(4) Process sensitivity index
This group of sensitivity indices indicate the influence of equipment and subassembly variants causing complexity to the single product key feature or the product family.

$$S^{y_i}_{\boldsymbol{U}^1,pro} = \frac{1}{M} \sum_{k=1}^{M} S^{\boldsymbol{y}_i}_{\boldsymbol{U}^1_{j,k}} \quad S^{Y}_{\boldsymbol{U}^1,pro} = \frac{1}{I} \sum_{i=1}^{I} S^{\boldsymbol{y}_i}_{\boldsymbol{U}^1,pro} \tag{24}$$

Similarly, we can get $S^{y_i}_{\boldsymbol{U}^2,pro}$, $S^{Y}_{\boldsymbol{U}^2,pro}$, $S^{\boldsymbol{y}_i}_{\boldsymbol{U}^3,pro}$, $S^{Y}_{\boldsymbol{U}^3,pro}$ and $S^{\boldsymbol{y}_i}_{\boldsymbol{C}^v,pro}$, and $S^{Y}_{\boldsymbol{C}^v,pro}$.

According to the above definition of the sensitivity indices, the key complexity source identifying and diagnosing process is established in Fig. 2.

6 Industrial case study

On the automobile body side wall welding line, station AFO090 (Fig. 3), AFO100 (Fig. 4), AFO110 (Fig. 5), and AFO120 (Fig. 6), namely, automatic positioned welding

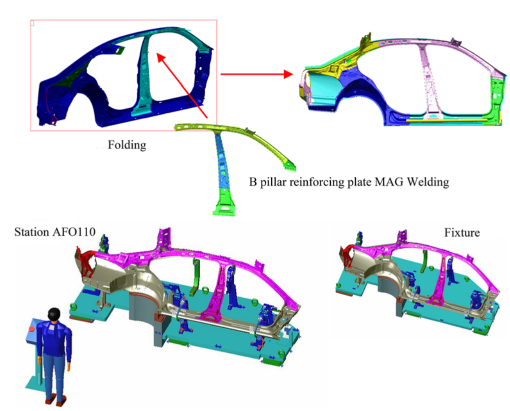

Fig. 5 Flanging and MAG welding station

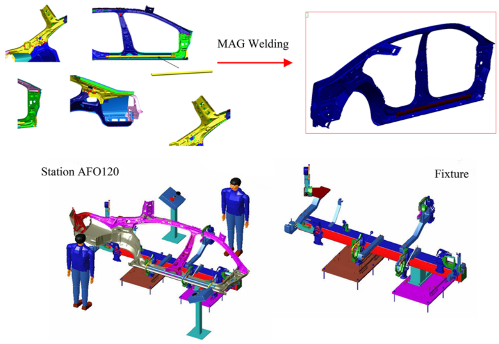

Fig. 6 Manual MAG welding station

station, respot welding and stud welding station, flanging station, and manual MAG welding station, respectively. Detailed informations on each station are shown in Table 1. Due to these four stations which are related to the position of all side wall subassembly, the complexity of these stations impact the quality of the final product, directly. We choose these four important stations as an industrial case for research.

Firstly, we take station AFO090 as an example, calculating the equipment complexity. According to the structural classification coding scheme mentioned in reference [19], welding equipment, material handling equipment, and buffer device are encoded according to type, structure, control mode, and operation mode. Encoding operation defines the information content of every equipment in auto-body welding line. So the complexity index of four welding robots on the station AFO090 are 0.810, 0.810, 0.810, and 0.433, respectively. The average complexity index I_e is 0.715. Wherein, the total quantity of equipment N_e is 4 and the quantity of unique equipment n_e is 4. According to the formula (1), the equipment complexity of welding equipment is 3.982. Through the same calculating process, the equipment complexity of material handling equipment and buffer device are 1.417 and 0. So the equipment complexity of station AFO090 is $C_i^E=\left[0,C_{\tilde{M}}^i,C_{\tilde{MHS}}^i,C_{\tilde{B}}^i\right]^T=[0,3.982,1.417,0]^T$. There are three subassembly variants assembling on the station AFO090; the demand proportion are 0.5, 0.3, and 0.2. According to the formula (5), the product subassembly selection complexity is $C_i^v=[C_i^v,0,0,0]^T=[1.485,0,0,0]^T$. Integrating equipment complexity and product subassembly selection complexity, according to the formula (7), the station-level integrated complexity is $C_i=C_i^{In}=C_i^v+C_i^E=[1.485,3.982,1.417,0]^T$, where i=AFO090. Through the same calculating process, the equipment complexity of station AFO100, AFO110, and AFO120 are $C_{i+1}^E=[0,3.927,1.444,0]^T$, $C_{i+2}^E=[0,3.143,1.444,0]^T$, and $C_{i+3}^E=[0,3.095,1.444,1.467]^T$. And the product subassembly selection complexity are $C_{i+1}^v=[1.485,0,0,0]^T$, $C_{i+2}^v=[1.485,0,0,0]^T$, and $C_{i+3}^v=[2.456,0,0,0]^T$. On the basis of the relationship matrix between subassembly variants and equipment selection given by the practical assembling instruction, we can get operator $\boldsymbol{\Phi}_{i,i+1}^e$. According to the formula (13), the station-level integrated complexity of station AFO100, AFO110, and AFO120 are $C_{i+1}=[1.485,5.858,3.300,0]$, $C_{i+2}=[1.485,4.405,2.520,0]$, and $C_{i+3}=[2.456,4.506,2.409,2.818]$. Based on the detailed description above, the complexity flow model of the process and system planning is established, and the result is shown in Table 2.

Based on the complexity flow model established above and combing the evaluated results of the experts with the tolerance of the equipment complexity source and product key characteristic, we can obtain the sensitivity indices of single equipment to single quality characteristic on each station by formula (17). Taking station AFO090 for instance, the sensitivity indices of welding robot 1 to quality characteristic 1, 2, 3, and 4 are 0.280, 0.460, 0.535, and 0.430, respectively. In accordance with formula (18), we can calculate the sensitivity index to product quality is 0.426. The sensitivity indices of welding equipment on station AFO090 to quality characteristic 1 are 0.280, 0.260, 0.325, and 0.115, respectively. On the basis of formula (19), the mean influence of the welding equipment complexity to quality characteristic 1 is 0.250. In the same

Table 1 Station description

Station	Component	Subassembly	Welding equipment	Handling equipment	Buffer device
AFO090: Side wall automatic positioned welding station	Side wall outer panel, flume, C pillar interior liner, and B pillar reinforcing plate	Side body subassembly	Three welding robots with different welding guns and one fixture	Desktop carrier	None
AFO100: Manual respot welding station	Side body subassembly	Side body subassembly	Four welding guns (3Type C, 1Type X) and one fixture	Hanger rail	None
AFO110: Manual flanging station	Side body subassembly	Side body subassembly	One flanging machine and one MAG welding gun	Hanger rail	None
AFO120: Manual positioned MAG welding station	Side body subassembly and stiffening tube	Side body subassembly	Two MAG welding guns, one fixture	Hanger rail	Storage box

Table 2 Process and system planning

Station	Class		Complexity index		Quantity of unique equipment	Total quantity of equipment	Complexity	Subassembly variants complexity	Station complexity
AFO090	Welding equipment	Welding robot and fixture	0.810 0.810 0.810 0.433	0.715	4	4	3.982	$1.485 = -(0.5 \times \log_2 0.5$ $+0.3 \times \log_2 0.3$ $+0.2 \times \log_2 0.2)$	$\begin{bmatrix} 1.485 \\ 3.982 \\ 1.417 \\ 0 \end{bmatrix}$
	Handling equipment	Desktop carrier	0.417		1	1	1.417		
	Buffer device	None	0		0	0	0		
AFO100	Welding equipment	Welding gun and fixture	0.534 0.534 0.534 0.534 0.500	0.519	5	5	3.927	1.485	$\begin{bmatrix} 1.485 \\ 5.858 \\ 3.300 \\ 0 \end{bmatrix}$
	Handling equipment	Hanger rail	0.444		1	1	1.444		
	Buffer device	None	0		0	0	0		
AFO110	Welding equipment	Flanging machine, MAG welding gun, and fixture	0.500 0.571 0.500	0.524	3	3	3.143	1.485	$\begin{bmatrix} 1.485 \\ 4.405 \\ 2.520 \\ 0 \end{bmatrix}$
	Handling equipment	Hanger rail	0.444		1	1	1.444		
	Buffer device	None	0		0	0	0		
AFO120	Welding equipment	MAG welding gun and fixture	0.571 0.571 0.500	0.548	3	3	3.095	2.456	$\begin{bmatrix} 2.456 \\ 4.506 \\ 2.409 \\ 2.818 \end{bmatrix}$
	Handling equipment	Hanger rail	0.444		1	1	1.444		
	Buffer device	Storage box	0.467		1	1	1.467		

Table 3 Complexity source identifying and diagnosing

Station	Class		Sensitivity index to quality characteristic 1		Sensitivity index to quality characteristic 2		Sensitivity index to quality characteristic 3		Sensitivity index to quality characteristic 4		Sensitivity index to product quality	
AFO090	Welding equipment and fixture	Welding robot 1	0.280	0.250	0.460	0.440	**0.535**	**0.451**	0.430	0.413	0.426	0.389
		Welding robot 2	0.260		0.540		0.372		0.320		0.373	
		Welding robot 3	0.325		0.260		0.455		0.550		0.398	
		Fixture	0.115		0.500		0.441		0.350		0.352	
	Material handling equipment	Trolley	0.005		0.006		0.010		0.008		0.007	
	Buffer device	None	0		0		0		0		0	
	Subassembly variants		0.150		0.200		0.175		0.175		0.175	
AFO100	Welding equipment and fixture	Welding gun 1	0.110	0.171	0.130	0.218	0.212	0.192	0.210	0.192	0.165	0.193
		Welding gun 2	0.150		0.200		0.173		0.120		0.161	
		Welding gun 3	0.200		0.160		0.110		0.150		0.155	
		Welding gun 4	0.115		0.170		0.143		0.230		0.163	
		Fixture	0.280		0.430		0.320		0.250		0.320	
	Material handling equipment	Hanger rail	0.010		0.005		0.004		0.005		0.006	
	Buffer device	None	0		0		0		0		0	
	Subassembly variants		0.150		0.220		0.175		0.175		0.175	
AFO110	Welding gun and fixture	Flanging machine	0.120	0.257	0.320	0.277	**0.535**	**0.454**	0.430	0.433	0.351	0.355
		Welding gun	0.220		0.180		0.372		0.320		0.273	
		Fixture	0.430		0.330		0.455		0.550		0.411	
	Material handling equipment	Hanger rail	0.010		0.005		0.004		0.005		0.006	
	Buffer device	None	0		0		0		0		0	
	Subassembly variants		0.150	0.200	0.175	0.175	0.175					
AFO120	Welding gun and fixture	Welding gun 1	0.211	0.242	0.250	0.263	0.200	0.270	0.195	0.243	0.214	0.255
		Welding gun 2	0.186		0.190		0.211		0.200		0.197	
		Fixture	0.330		0.350		0.400		0.335		0.354	
	Material handling equipment	Hanger rail	0.010		0.005		0.004		0.005		0.006	
	Buffer device	Storage box	0.005		0.006		0.008		0.010		0.007	
	Subassembly variants		0.215		0.232		0.185		0.190		0.206	
Process sensitivity index	Welding equipment and fixture		0.230		0.298		**0.342**		0.320		**0.298**	
	Material handling equipment		0.009		0.005		0.006		0.006		0.007	
	Buffer device		0.001		0.002		0.002		0.003		0.002	
	Subassembly variants		0.166		0.208		0.178		0.179		0.183	

way, the mean influence of the welding equipment complexity to quality character 2, 3, and 4 are 0.440, 0.451, and 0.413, respectively. Finally, from formula (20), the sensitivity index of welding equipment complexity to product quality is 0.389. Process sensitivity indices can be calculated by formula (24). At last, through sensitivity index analysis process, the complexity source is identified and diagnosed. Key station and key equipment are identified, and the result is shown in Table 3. The key station and key equipment are highlighted. Based on the result, we can make more detailed process planning or select more robust and appropriate equipments.

Based on the complexity source sensitivity index calculation process, we find the welding equipment process sensitivity index maximum value is that $S^{\boldsymbol{Y}}_{\boldsymbol{U}^1,pro} = 0.298$. And because $S^{y_3}_{\boldsymbol{U}^1,pro} > 1.145 S^{\boldsymbol{Y}}_{\boldsymbol{U}^1,pro}$, then we prefer the index is that $S^{y_3}_{\boldsymbol{U}^1,pro} = 0.342$. According to the calculation result listed in the Table 3 and the above analysis, AFO110 is located as the complexity source key station, and at this station, the flanging machine is identified as the key complexity source. Therefore, it is important to pay attention to the selection and operation of flanging machine, to improve the quality of final auto-body side product. Secondly, minor key station is AFO090, the automatic positioning welding station. At this station, welding robot 3 is determined as the key complexity source. So much attention should be payed to the welding holder selection and PLC program of this welding robot 3 to improve the quality of final auto-body side product.

7 Summary

In this paper, within the auto-body mixed model welding line, based on the structural classification coding of equipment, and combining the personalized component information, we propose the station-level integrated complexity model, integrating the equipment complexity and product subassembly selection complexity. The former one includes the complexity of welding equipment, material handling equipment, and buffer device. Then, based on the application of state space theory, the system-level complexity flow model is constructed, which indicates the transformation of personalized subassembly information in mixed model welding line. It is conducive to identify and control the complexity source of the auto-body welding line which becomes an effective decision-making tool to the assembly system process planner. Therefore, the planning scheme will get a reasonable complexity so that it can effectively reduce the cost of the welding line, save the time, and enhance the product quality and productivity, to promote further the profit and competitiveness of the manufacturer.

Finally, we establish various sensitivity indices that are welding equipment sensitivity index, material handling equipment sensitivity index, buffer device sensitivity index, and subassembly variants causing complexity sensitivity index. These indices indicate the contribution of complexity source to the final evaluation. We also propose a process of identifying and diagnosing the complexity source within the process planning. Through sensitivity analysis, we can get the response of system output to the input complexity source and determine which and where the process and equipment information will affect the transformation of the complexity. Based on the method above, the planner can minimize the sensitivity indices through comparing and changing the process and system planning, so that the planning is more robust to these complexity source.

Based on application of auto-body side welding line case, the result indicates that the proposed complexity model and key complexity source identifying and diagnosing process can be used as decision support tool of auto-body welding system.

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