COUPLING MODEL OF EXTENDED MANUFACTURING ORGANIZATION AND ITS APPLICATION

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Abstract: For the feature of complex weapon manufacturing on internet, a coupling model is proposed. By using the model, the correlation between manufacturing cells in an extended manufacturing organization can be evaluated quantitatively, so an appropriate control plan is determined. A strategy to improve and reduce the coupling relationship of the organization is studied. A correlation matrix of extended tasks is built to analyze the relationship between sub-tasks and manufacturing resources. An optimization method for manufacturing resource configuration is presented based on the coupling model. Finally, a software system for analyzing coupling model about manufacturing organization on internet is developed, and the result shows that the coupling model is effective.

Key words: networked manufacturing; manufacturing organization; correlation matrix; coupling model

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INTRODUCTION

Networked manufacturing is one of development tendencies of advanced manufacturing, and according to special requirements, there are several derivations of the networked manufacturing model, such as virtual enterprise[1], networked manufacturing based on ASP[2], and collaborative manufacturing chain[3]. These models mostly adopt the loose coupling management and emphasize the autonomy of enterprises, but some problems still exist, such as, the confidentiality cannot be assured in the manufacturing process, the manufacturing progress cannot be kept abreast of the times, and quality problems cannot be tracked, etc. Therefore they cannot satisfy the controllability, measurability and reliability requirements of manufacturing process for complex armament. Extended manufacturing[4] is a new networked manufacturing model and orients to the rapid production of complex armament. The construction method of extended manufacturing organization based on coupling is proposed in this paper.

At present, design task planning of the complex product based on the coupling arouses great attention of researchers. Ref. [5] presented a process model with structure of design structure matrix family based on the study of design structure matrix. Ref. [6] developed an effective model to transform the binary task relation into the quantifiable task coupling length and decompose the large interdependent task group into smaller and manageable sub-groups. Ref. [7] developed a method for measuring functional dependency and sequencing of coupled tasks in engineering design to improve the design process. But there are few researches for manufacturing domain. In order to clearly discuss the extended manufacturing coupling and construction process, some definitions are given as follows:

Definition 1 Networked manufacturing coupling. Networked manufacturing tasks are undertaken by manufacturing resources distributed in different areas. Due to differences in organiza-

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tional structure, production practices, information platform, and geographical location among different enterprises, the continuous manufacturing process performed in one enterprise is divided into several discrete manufacturing nodes in the whole network. Two or more manufacturing nodes interact and influence the whole manufacturing system. This is called networked manufacturing coupling.

Definition 2 Extended nodes (ENs). It refers to those extended manufacturing resources (ERs) that are able to afford extended tasks (ETs) delivered by the dominant enterprise. ENs can be expressed as the following formula

$$\mathrm{EN} ::= \{\mathrm{ET}, \mathrm{ER}\}$$

The coupling in networked manufacturing is due to the manufacturing tasks distributed in different places discretely, and there is the stronger coupling between extended manufacturing nodes. Two reasons are listed as follows:

(1) The complex manufacturing process. Due to the particular requirements in security, quality and schedule, all suppliers are brought into the extended manufacturing system, thus a controllable organization in whole manufacturing is constructed. ETs are undertaken by different ERs, so raw material, semi-finished and finished products are transmitted between different ENs, and a complex and huge network for material transmission is formed.

(2) The complex tasks. The development of complex armament is a technology-intensive engineering. For example, a plane is composed of millions of parts, and during the manufacturing process, the quality of parts should be ensured and the coordination between ETs should be satisfied, such as the manufacturing coordination between different processes of one part, and assembly coordination between parts. Hence, lots of information should be transmitted between the dominant enterprise and ERs in order to coordinate production schedule and control product quality.

Complex transmission of material and information cause many difficulties for the dominant enterprise to control the manufacturing process and the coordinate between ERs. If there is random disturbance during the manufacturing process in one ENs, the production schedule and the product quality of the others are affected too. So the closely-related ETs are performed by closely-related ERs, thus enhancing the coupling between ERs. It makes easy for manufacturing, assembly, debugging, and maintenance, reduces the bad impacts of interruption during manufacturing process, and improves controllability, measurability and reliability of the extended manufacturing process.

The construction of extended organization is divided to two steps. One is reduce-coupling decomposition strategy, i. e., closely-related ETs are grouped into clusters to reduce the effect of complex ETs correlation and improve the independence of ETs and the parallelism during manufacturing process. The other is improve-coupling allocation, i. e., on the basis of the reduce-coupling decomposition, the dominant enterprise chooses closely-related ERs for ETs in the same clusters.

1 MATCHING FOR ETs AND ERs

Supposing that n_{T} is the totality of ETs and n_{R} is the totality of ERs. Several ERs having the manufacturing capability can be retrieved to match the manufacturing requirements of ETs, so the matching relation of one ET to several ERs is formed, as shown in Fig. 1①. $\mathrm{ER}_{i\_p}(p=1,2,\cdots,n_{i\_R})$ represent that the extended resource p has the capability to fulfill task i, and n_{i_R} is the totality of resources capable of fulfill task i.

2 REDUCE-COUPLING STRATEGY

The reduce-coupling strategy includes two steps, which is the correlation analysis of ETs and the reduce - coupling decomposition based on

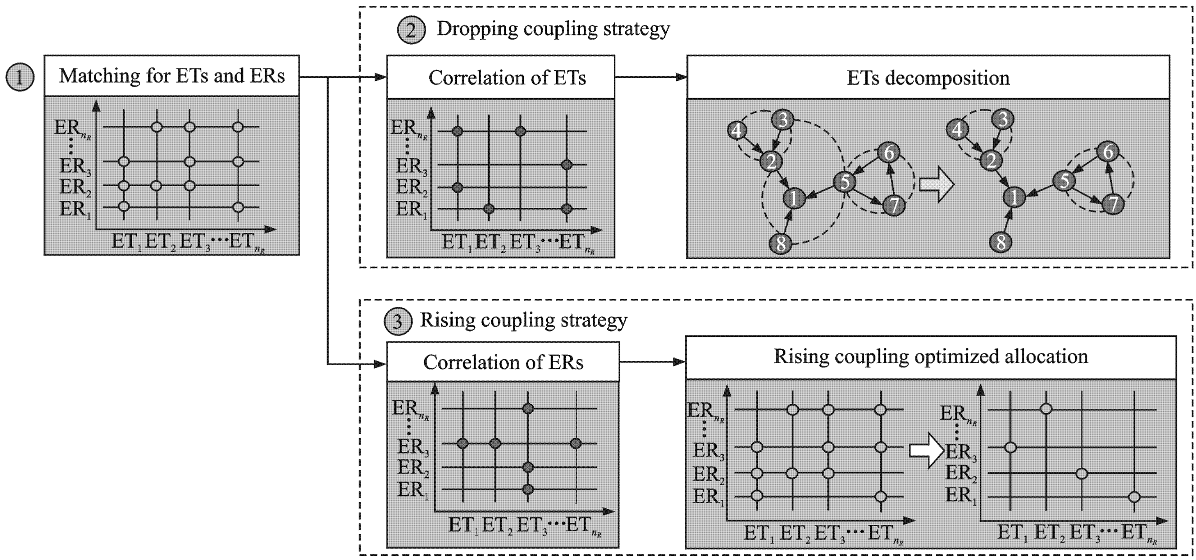


Fig. 1 Construction process of extended manufacturing

correlation of ETs as shown in Fig. 1②.

2.1 Correlation analysis of ETs

The complex relations between ETs are the reasons for coupling in extended manufacturing. In order to explain the correlation of ETs, it is classified into two categories as follows:

(1) **Correlation** Ⅰ The material transmission correlation.

Due to the limit of due date and the manufacturing capability, the finished ETs should be transmitted to other ERs in order to finish the next manufacturing or assembly tasks. Supposing that $f_{ij} \in \{0,1\}$ is the value of material transmission correlation. $f_{ij}=1$ represents that there is a correlation between ET_i and ET_j, i. e., the finished ET_i should be transmitted to another ER to finish ET_j. $f_{ij}=0$ represents that there is no correlation.

(2) **Correlation** Ⅱ Correlation besides material transmission.

① The assembly coordination: Lots of parts are assembled into complex products, and several factors such as assembly accuracy, assembly sequence, assembly interference, and production schedule of parts in different enterprises, can affect the product quality and the due date, so parts with assembly relations have stronger correlation.

② Manufacturing process correlation: Many manufacturing processes of complex parts need to be finished in different ERs, so manufacturing processes of the same part have stronger correlation.

③ Function realization correlation: In order to realize a sub-function of a product, parts should coordinate with each other, and power, data and signal are transmitted between them. It is convenient for function debugging if the parts are sent to ERs with a closer relationship. So, the production and assembly tasks with function realization relationship have stronger correlation.

Supposing that $r_{Tmij}(m=1,2,3)$ are the indexes of coordination, manufacturing process, and function realization correlation respectively between ET_i and ET_j. According to the importance or closeness of relationship, r_{Tmij} is ranked into six levels[8], i. e., $r_{Tmij} \in$ {no correlation, the weakest, weaker, mediate, stronger, the strongest} = {0, 0.2, 0.4, 0.6, 0.8, 1}, so the degree of correlation Ⅱ can be calculated by using Eq. (1).

$$r_{T\mathrm{II}ij} = \begin{cases} \sum_{m=1}^{3} \omega_{Tm} r_{Tmij} & i \neq j \\ 1 & i = j \end{cases} \quad (1)$$

where $r_{T\mathrm{II}ij}$ is the degree of correlation Ⅱ between ET_i and ET_j, $\omega_{Tm}(m=1,2,3)$ are the weight of correlation Ⅱ.

The correlation model can be established by correlations Ⅰ and Ⅱ. Supposing that f_{ij} is in the first quadrant, and r_{Tij} is in the second quadrant, as shown in Fig. 2.

	ET_j	
$r_{Tij}=ET_i$	Correlation Ⅰ f_{ij}	Correlation Ⅱ $r_{T\text{Ⅱ}ij}$

Fig. 2 Correlation model of ETs

In Fig. 3, an example is given to explain the model. Solid lines represent the transmission direction of material, and dotted lines indicate the second correlation existed between different ETs. The manufacturing process includes seven ETs. ET_0 is product assembly, which is completed in the dominant enterprise; ET_1 is component assembly, which assembles the parts manufactured by ET_2 and ET_3; ET_4 is a part of manufacturing task; ET_5 and ET_6 are the processes of ET_4. It should be noted that all the above tasks are completed in ERs. The correlation matrix is shown in Fig. 4.

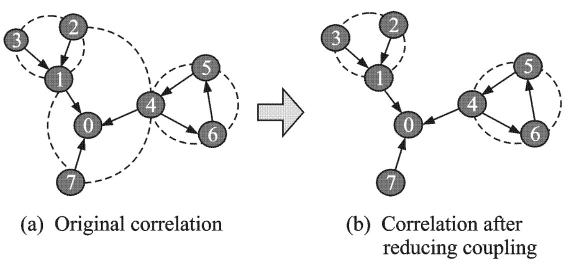


Fig. 3 Correlation directed graph of ETs

$\boldsymbol{R}_T=[r_{Tij}]_{n_T\times n_T}=$

	0	1	2	3	4	5	6	7
0	0|1							
1	1|0	0|1	0|0.9	0|0.8				0|0.3
2		1|0.9	0|1	0|0.7	0|0.4			
3		1|0.8		0|1				
4	1|0		0|0.4		0|1	0|0.8	1|0.7	0|0.3
5					1|0.8	0|1	0|0.8	
6					0|0.7	1|0.8	0|1	
7	1|0	0|0.3			0|0.2			0|1

Fig. 4 Matrix model of ETs correlation

2.2 Reduce-coupling decomposition based on correlation Ⅱ of ETs

ETs based on correlation II are decomposed by fuzzy clustering[9], i. e., ETs with stronger correlation are grouped into the same cluster, and the weaker relationship between ETs is eliminated, so clusters consisting of ETs with strong correlation can be formed. The value type of correlation Ⅱ is also transformed from Numeric to Boolean, this is $r'_{T\text{Ⅱ}ij}\in\{0,1\}$. If ETs in the same cluster have strong correlation Ⅱ, $r'_{T\text{Ⅱ}ij}=1$; otherwise, $r'_{T\text{Ⅱ}ij}=0$.

As shown in Fig. 3(b), after the reduce-coupling decomposition for the seven ETs, the correlations between ET_3 and ET_4, ET_1 and ET_7 are eliminated. ET_7 is an independent task, thus three clusters {1,2,3},{4,5,6},{7} are formed, and the process of decomposition is shown in Fig. 5.

	1	2	3	4	5	6	7
1	1	0.9	0.8				0.3
2	0.9	1	0.7	0.4			
3	0.8		1				
4		0.4		1	0.8	0.7	0.2
5				0.8	1	0.8	
6				0.7	0.8	1	
7	0.3			0.2			1

⇨

	1	2	3	4	5	6	7
1	1	1	1				
2	1	1	1				
3	1	1	1				
4				1	1	1	
5				1	1	1	
6				1	1	1	
7							1

Fig. 5 Decomposition process of correlation matrix based on correlation Ⅱ

3 IMPROVE-COUPLING STRATEGY

The correlation between ERs determines the degree of coupling between ENs, so the correlation between ERs should be considered in order to realize the improve-coupling allocation, by which the extended organization based on "the whole process controlled" is constructed. The improve-coupling strategy includes two steps: the correlation analysis of ERs and the improve-coupling optimization allocation, as shown in Fig. 1③.

3.1 Correlation analysis of ERs

Tighter coupling between ENs produces better communication and coordination between ERs, so enhancing the coupling between ENs is an effective method to improve controllability, measurability and reliability of manufacturing process. The correlation of ERs is classified into two categories as follows:

(1) **Correlation** Ⅰ Geographic distance correlation.

Geographic distance between ER_p and ER_q (d_{1pq}) also affects the possibility for cooperation. The shorter d_{1pq} comes less transport time and cost, and vice versa.

(2) **Correlation** Ⅱ The correlation besides geographic distance.

① The manufacturing capability: The manufacturing capability is one of the key factors that determine the cooperating willingness of ERs. The stronger manufacturing capability the ER have, the more cooperation opportunities it enjoys, and vice versa. Several indices that reflect the manufacturing capability can be considered, such as, manufacturing time (T), manufacturing cost (C), product quality (Q). r_{R1pq} is defined as correlation manufacturing capability between ER_q and ER_p. The larger the r_{R1pq} is, the stronger manufacturing capability the ER_q has, and the easier the ER_q is chosen as the cooperator of the ER_p. The enterprise strength of EE_q has the same effect on another enterprise, so r_{R1pq} in the same column of $\boldsymbol{R}_{R1}$ is identical. The value r_{R1pq} is from 0 to 1 by expert scoring method, and the better cooperation results in higher score. The correlation matrix of manufacturing capability is shown in Eq. (2).

$$\boldsymbol{R}_{R1}=[r_{R1pq}]_{n_R\times n_R}=\begin{pmatrix} r_{R1(11)} & r_{R1(12)} & \cdots & r_{R1(1n_R)} \\ r_{R1(11)} & r_{R1(12)} & \cdots & r_{R1(1n_R)} \\ \vdots & \vdots & \ddots & \vdots \\ r_{R1(11)} & r_{R1(12)} & \cdots & r_{R1(1n_R)} \end{pmatrix} \tag{2}$$

② The industry correlation: There are many similarities in resource types like technicians, equipment and information platform, and in production habit between the extended enterprises in identical or related industry. After accepting the manufacturing tasks, the enterprises in identical or related industry can perform the tasks without changing much of the existing production condition. This can meet the requirement of rapid response to armament production. According to the Industrial Classification of National Economic Industries (GB/T4754—2002) enacted by General Administration of Quality Supervision, Inspection and Quarantine, an industry structure tree is constructed, as shown in Fig. 6.

According the method introduced in Ref. [10], the industry correlation between enterprises can be obtained. Supposing that l_i and l_j represent the distance between the position of the industry of ER_p, ER_q and their common parent node in Fig. 7, and $x=\frac{1}{2^{l_p+l_q-2}}$, then the industry correlated degree can be calculated by Eq. (3). r'_{R2pq} is normalized by using $r_{R2pq}=\frac{r'_{R2pq}-r'_{R2pq(\min)}}{r'_{R2pq(\max)}-r'_{R2pq(\min)}}$, and $r_{R2pq}\in[0, 1]$.

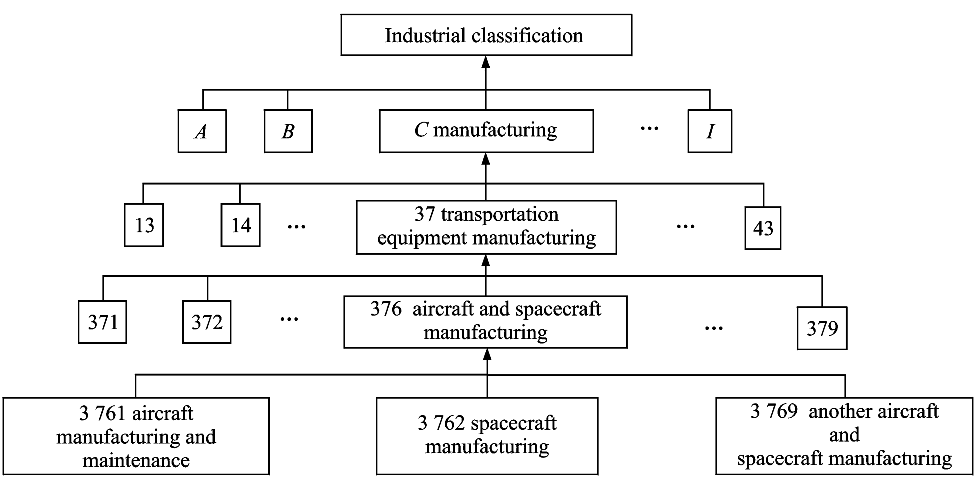


Fig. 6 Industry structure tree

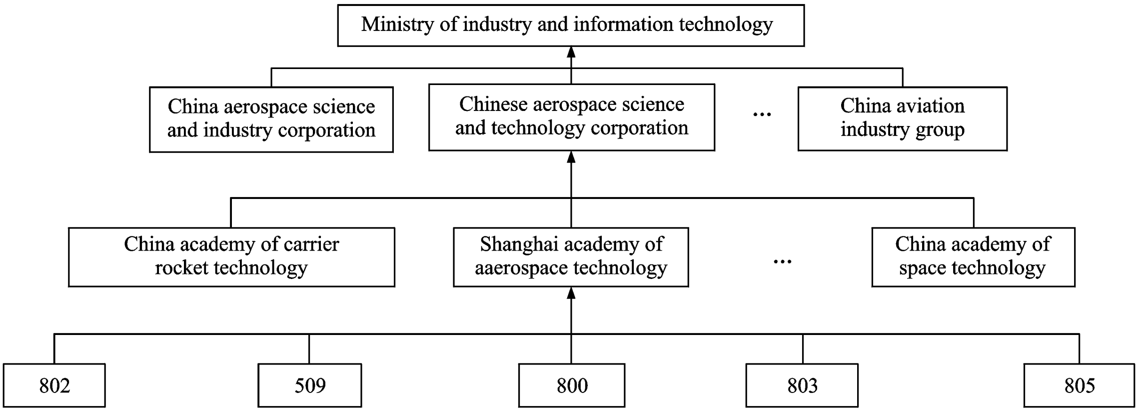


Fig. 7 Affiliation structure tree

$$r_{R2pq} = \begin{cases} x & x \geqslant 0.25 \\ 0 & x < 0.25 \end{cases} \tag{3}$$

③ The affiliation correlation: The enterprises in the same group have the same higher authority, and it is easy for technicians to find out and solve problems in the manufacturing process, thus making extended manufacturing process much smoother. The affiliation structure tree is shown in Fig. 7. In reference to the solution method of r_{R3pq}, the affiliation correlated degree r_{R3pq} can be obtained. So the degree of correlation II can be calculated using Eq. (4). The correlation Ⅱ matrix is shown in Eq. (5)

$$r_{R\,\mathrm{II}\,pq} = \begin{cases} \sum_{m=1}^{3} \omega_{Rm} r_{Rmpq} & p \neq q \\ 1 & p = q \end{cases} \tag{4}$$

$$\boldsymbol{R}_{R\,\mathrm{II}\,pq} = [r_{R\,\mathrm{II}\,pq}]_{n_R \times n_R} \tag{5}$$

where $r_{R\,\mathrm{II}\,pq}$ is the degree of correlation Ⅱ between ER_p and ER_q, and $\omega_{Rm}(m=1,2,3)$ are the weight of correlation Ⅱ.

The distance based on correlation Ⅱ can be obtained by using Eqs. (6,7).

(1) Before the distance calculation, the effect on distance should be reduced through normalizing processing, so

$$r'_{R\,\mathrm{II}\,pq} = (r_{R\,\mathrm{II}\,pq} - \sum_{j=1}^{n} \frac{r_{R\,\mathrm{II}\,pq}}{n}) / \mathrm{STD}(r_{R\,\mathrm{II}\,pq}) \tag{6}$$

where STD is maximum difference normalization formula.

(2) $d_{\mathrm{II}\,pq}$ stands for the "distance" between extended enterprises ER_p and ER_q, which is the possibility for cooperation between ER_p and ER_q. The smaller $d_{\mathrm{II}\,pq}$, the more possibility for cooperation, and vice versa. The distance $d_{\mathrm{II}\,pq}$ can be calculated using Euclid distance Eq. (7).

$$d_{\mathrm{II}\,pq} = \left(\sum_{k=1}^{n} (r'_{R\,\mathrm{II}\,pk} - r'_{R\,\mathrm{II}\,qk})^2 \right)^{1/2} \tag{7}$$

The distance based on correlation Ⅱ matrix $\boldsymbol{D}$ can be constructed corresponding to the correlation matrix $\boldsymbol{R}_{R\,\mathrm{II}\,pq}$. , as shown in Eq. (8).

$$\boldsymbol{D}_{\mathrm{II}\,pq} = \begin{pmatrix} 0 & & & \\ d_{\mathrm{II}(21)} & 0 & & \\ \vdots & \vdots & 0 & \\ d_{\mathrm{II}(n1)} & d_{\mathrm{II}(n2)} & \cdots & 0 \end{pmatrix} \tag{8}$$

The correlation model can be established by correlations Ⅰ and Ⅱ. d_{pq} is in the first quadrant, and $d_{\mathrm{II}\,pq}$ is in the second quadrant, as shown in Fig. 8.

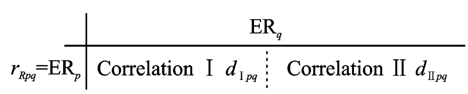


Fig. 8 Correlation model of ETs

3.2 Improve-coupling optimization allocation

Besides manufacturing capability existing in usual method of resource optimization allocation, resource correlation is also taken into consideration in improve-coupling resource allocation, thus making it a multi-objective allocation strategy, which is more complex than the traditional resource allocation. The optimization objectives based on resources correlation are analyzed as follows.

(1) When the dominant enterprise selects ERs as its cooperators, the correlation Ⅱ between ERs (Eq. 9) need to be considered.

$$O_1 = \sum_{i=1}^{n_T} d_{\mathrm{II}(i\_p)} \quad p = 1,2,\cdots,n_{i\_R} \tag{9}$$

where $r_{R\mathrm{II}(i\_p)}$ is the distance based on correlation Ⅱ between the dominant enterprise and ERs.

(2) Closely-related ERs should be allocated for ETs in the same cluster ($r'_{T\mathrm{II}ij}=1$), so the coupling between ENs is enhanced. Coordination between ENs is made easily, and the production schedule and quality of product can be ensured. The distance based on correlation II between ER_{i_p} and ER_{j_q} is shown as follows

$$O_2 = \sum_{i=1}^{n_T}\sum_{j=1}^{n_T}\frac{1}{2}\cdot r'_{T\mathrm{II}ij}\cdot d_{\mathrm{II}(i\_p,j\_q)}$$
$$i \neq j,\ p = 1,2,\cdots,n_{i\_R},\ q = 1,2,\cdots,n_{j\_R} \tag{10}$$

(3) The geographical distance from ER_{i_p} to ER_{j_q} can be calculated by using Eq. (11)

$$O_3 = \sum_{i=1}^{n_T}\sum_{j=i}^{n_T} f_{ij}\cdot d_{\mathrm{I}(i\_p,j\_q)}$$
$$i \neq j,\ p = 1,2,\cdots,n_{i\_R},\ q = 1,2,\cdots,n_{j\_R} \tag{11}$$

According to the above analysis, a mathematic model of improve-coupling optimization allocation is formulated as

$$\min F = \omega_1\cdot\lambda_1\cdot O_1 + \omega_2\cdot\lambda_2\cdot O_2 + \omega_3\cdot\lambda_3\cdot O_3 \tag{12}$$

where ω_m ($m=1,2,3$) are the weight and for O_1, O_2, O_3, λ_m ($m=1,2,3$) are standardized coefficients to eliminate morbid effects of dimension.

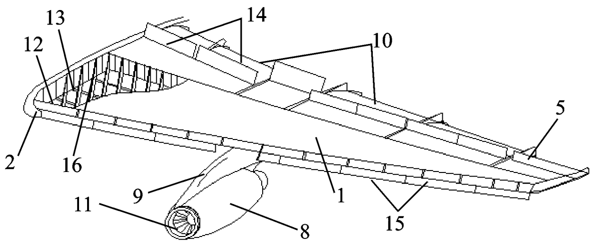
$$\sum_{m=1}^{3}\omega_m = 1 \tag{13}$$

Genetic algorithm (GA) is adopted for the realization of resource allocation based on correlation, and the construction of the extended organization details of GA is not discussed in this paper.

4 CASE STUDY

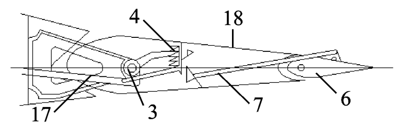
The structures of a wing of aircraft are shown in Fig. 9. The manufacturing tasks need to be extended to external enterprises.

Firstly, the correlation of ETs is analyzed,



1—skin; 2—wing; 5—aileron; 8—engine; 9—engine mount; 10—flag; 11—blade; 12—spar; 13—beam; 14—spoiler; 15—slat; 16—wing rib

(a) Structure of wing



3—rocker arm; 4—spring; 6—servo-compensator; 7,17—pull rod; 18—aileron

(b) Structure of aileron

Fig. 9 Structures of wing and aileron

and the correlation matrix is shown in Fig. 10. Weak correlation is eliminated by using the method of reduce-coupling decomposition, and five clusters are formed: {1,2,5,10}, {3,4,6}, {8,11}, {7}, {9}.

Secondly, the improve-coupling process consists of two steps: (1) The information of ERs is input, including manufacturing capability, industry, affiliate, and geographic position, so the degree of correlation can be obtained. (2) Through the improve-coupling allocation, the extended organization based on tight coupling can be constructed. In the extended manufacturing process, the dominant enterprise and ERs supervise production schedule, record and analyze quality data by using management tools of coordinative plat-

	0	1	2	3	4	5	6	7	8	9	10	11
0												
1		1	1|0.85			0.7					0.7	
2	1|0	0.85	1			0.85					0.85	
3				1	0.75		1|0.85					
4				0.75	1		1|0.75					
5		0.7	1|0.85			1					0.5	
6	1|0			0.85	0.75		1	0.5				
7	1|0						0.5	1				
8	1|0								1	0.5		1|0.95
9	1|0								0.5	1		0.3
10	1|0	0.7	0.85			0.5					1	
11									1|0.95	0.3		1

Fig. 10 Correlation matrix of ETs

form, which ensures the normal operation of extended manufacturing.

5 CONCLUSION

The coupling of extended manufacturing is studied in the paper, and the features of the coupling model are analyzed, by which a method for building manufacturing organization on internet is put forward. And a system of extended manufacturing allocation based on coupling model is developed. Finally, a case is given to show the validation of the coupling theory. Results show that the theory can greatly improve rationalization and optimization of decision about how to organize the manufacturing resources. But the theory of coupling is not fully mature, especially in how to abstract the coupling relationship between different manufacturing organizations on internet. So many problems need to be studied to refine the theory.

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扩散制造组织中的耦合模型及其应用

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摘要:针对复杂武器装备网络化制造的特点,提出了一种耦合度模型。该模型可以定量地描述扩散企业中各个制造单元间的关联程度,从而确定适当的控制策略。同时研究了网络化制造组织的升耦和降耦策略,并从中提出了扩散制造任务关联矩阵的概念,用于分析和计算子任务和网络化制造资源的耦合度。基于以上分析,给出了基于耦合度分析的网络化制造资源优化配置方法。最后,开发了一个用于分析网络化制造组织耦合度的软件,并通过实例研制了该方法的有效性。

关键词:网络化制造;制造组织;关联矩阵;耦合模型

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