Modeling and Decoupling of Coupling Tasks in Collaborative Development Process of Complicated Electronic Products

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Abstract: It is important to improve the development efficiency of decoupling a coupling task package according to the information relevancy relation between development tasks in the collaborative development process of complicated electronic products. In order to define the task coupling model in the development process, the weighted directed graph based on the information relevancy is established, and the correspondence between weighted directed graph model and numerical design structure matrix model of coupling tasks is introduced. The task coupling model is quantized, thereby the interactivity matrix of task package is built. A multi-goal task decoupling method based on improved genetic algorithm is proposed to decouple the task coupling model, which transforms the decoupling of task package into a multi-goal optimization issue. Then the improved genetic algorithm is used to solve the interactivity matrix of coupling tasks. Finally, the effectiveness of this decomposition method is proved by using the example of task package decoupling of collaborative development of a radar's phased array antenna.

Key words: task coupling model; task decoupling; weighted directed graph; design structure matrix; genetic algorithm

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0 Introduction

At present, to satisfy users' requirements for multiple function and high performance, complicated electronic products (CEP) are becoming more interactive, higher integrated and smaller sized, so the related development process has become more complex. Concurrent order, serial order and coupling relationship exist among development tasks[1]. If coupling is excessive among task and not decoupled, a huge team is necessary to uniformly implement these tasks, and a lot of expense and time will be cost. As a result, as for product development task package with overly complicated coupling, it needs to be decoupled to simplify the coupling relation among tasks.

With regard to product development, the main modeling approaches at present include directed graph (DG), critical path method (CPM), programme evaluation and review technique (PERT), integration definition (IDEF) series modelling, Petri net and design structure matrix (DSM)[2-3]. DG is a rather direct modelling tool for it can be easily understood in expressing information delivery relation among development tasks. Although DG doesn't adequately describe the coupling strength among tasks, by adding node attributes or weighing arc[4], researchers can expand DG and establish the relational mapping between DG and DSM[5-6]. The modelling capacity of DG will be strengthened in product development by adopting these methods. Meanwhile, as another kind of effective modelling tool in product development[7], DSM can be applied

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to make up for the shortage of DG modelling with its more compact expression form and more flexible mathematical method. DSM can be reconstructed through matrix transformation so as to analyze the task sequence and entire structure of the development process[8-9]. Yassine and Braha[1] have adopted DSM to explain four key words in implementing concurrent engineering during the development of complicated products - iteration, repetition, disintegration/integration and convergence. Numeric DSM[8,10-11] is an important tool to quantize the relation among product development activities. Luh et al.[12] have set up fuzzy DSM, and applied fuzzy clustering method for quantizing the information flow of activity elements in new product development. Based on quantization, coupling task in product development can be decoupled and optimized. Chen and Lin[13] have adopted numeric DSM to transform the binary coupling relation into the numeric relation, and then applied Euclidean distance to decouple task package. Ref.[14] has constructed a multidisciplinary coupling strength model of product design by fuzzy DSM, and then proposed a method of decoupling and planning of multidisciplinary coupling. Ref.[15] has applied gray DSM to present the coupling relation of design tasks quantitatively and hence realized the decoupling. Ref.[16] has expounded the correspondent relation between DG and DSM in product design process, and reconstructed and optimized design process based on path searching method. Ref.[17] has used DSM to model collaborative design of space science mission, and adopted the genetic algorithm to optimize the design process.

In above research, DG is generally based on empirical value for quantitated weigh, and the physical significance of corresponding relation between directed graph model and DSM model in product development has not been explained. Besides, there is no complete systematic method of coupling task modelling and decoupling. As a result, it's necessary to carry out a systematic research on modelling and decoupling of tasks coupling. Based on tasks in the collaborative development process of CEP, the thesis has adopted information - relevancy - based weighted directed graph (WDG) to analyze the relation of information delivery among tasks quantitatively and then established task coupling model (TCM). In addition, the corresponding relation between WDG and numeric DSM is adopted to unify them. According to the interactivity matrix of coupling task package, the thesis puts forward a multi-goal task decoupling method based on the improved genetic algorithm. First of all, task package decoupling will be transformed into multi-goal optimization issue. Then, the improved genetic algorithm will be applied for the solution. Lastly, through the example of task decoupling in collaborative development process of radar's phased array antenna, the method is verified.

1 Establishment of TCM in the Process of CEP Collaborative Development

1.1 TCM using WDG based on information relevancy

The development process of CEP consists of a series of development tasks, and each task is more or less in need of information provided by other tasks for implementation. A task can not be initiated unless it has the necessary information for execution. Mutual delivery and effect of information among tasks are decisive to the development process of complicated electronic product. Therefore, the relation among collaborative development tasks of complicated electronic product is essentially information relevant and can be presented by information relevancy value. In order to directly express it, the WDG is used for modelling this information relevancy relation.

Definition 1 Among task set of in the collaborative development process of CEP, supposing that the development tasks are T_i and T_j (i, $j=1, 2, \cdots, N$; $i \neq j$), the information delivery model between development tasks T_i and T_j (Fig.1) can be presented by directed graph Φ, which is

$$\Phi = (T_j, (T_j, T_i), T_i) \tag{1}$$

where $(T_j, (T_j, T_i), T_i)$ is a chain from T_j to T_i, and

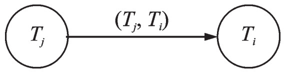

Fig.1 Information delivery model between T_i and T_j

(T_j, T_i) is a directed arch in Φ. With respect to information input and output, arch (T_j, T_i) can be divided into: $(T_j, T_i)^i$ means information input by T_j and accepted by T_i , $(T_j, T_i)^j$ is information output by T_j to T_i.

Definition 2 In (T_j, T_i), p_{ij} stands for the information amount input by T_j and accepted by T_i, which is

$$p_{ij}=w(T_j,T_i)^i \tag{2}$$

q_{ij} is the information amount output by T_j to T_i, which is

$$q_{ij}=w(T_j,T_i)^j \tag{3}$$

Definition 3 Information value delivered from T_j to T_i equals to the geometric mean of p_{ij} and q_{ij}, which is called the information relevancy from T_j to T_i. Namely the weight of directed arch (T_j, T_i) can be denoted as r_{ij}, which is

$$r_{ij}=\sqrt{p_{ij}q_{ij}}=w(T_j,T_i) \tag{4}$$

when $i=j$, $r_{ij}=0$.

Based on the definition of information delivery model and information relevancy between task T_i and task T_j, the TCM of CEP in collaborative development process can be defined.

Definition 4 The TCM of CEP in collaborative development process is a two-tuples, which is

$$\mathrm{TCM}=\langle\Psi,\Omega\rangle \tag{5}$$

where Ψ and Ω are two WDGs.

$$\Psi=\left\{\Phi_n^{(i)}|n=1,2,\cdots,k\right\} \tag{6}$$

$$\Omega=\left\{\Phi_n^{(j)}|n=1,2,\cdots,l\right\} \tag{7}$$

In Eq.(6), $\Phi_n^{(i)}$ is a chain of WDG Ψ (Fig.2).

$$\Phi_n^{(i)}=(T_{jn},(T_{jn},T_i)^i,T_i) \tag{8}$$

where T_i stands for the task node of receiving information input and T_{jn} $(n=1, 2, \cdots, k)$ is one of all task nodes which provide information to T_i. Weighed $w(T_{jn}, T_i)^i$ of directed arch $(T_{jn}, T_i)^i$ equals to p_{ijn}, which stands for the input information amount accepted by T_i from T_{jn}.

In Eq.(7), $\Phi_n^{(j)}$ is a chain of WDG Ω (Fig.3), which can be expressed as

$$\Phi_n^{(j)}=(T_j,(T_j,T_{in})^j,T_{in}) \tag{9}$$

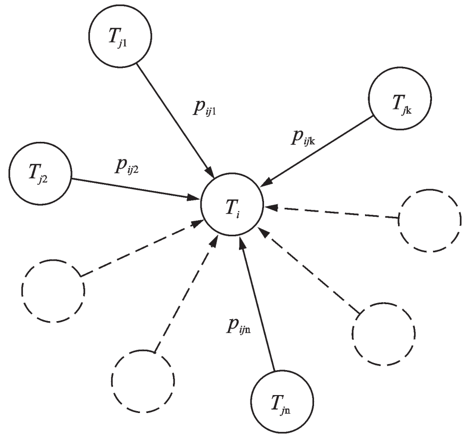

Fig.2 Weighted directed graph Ψ

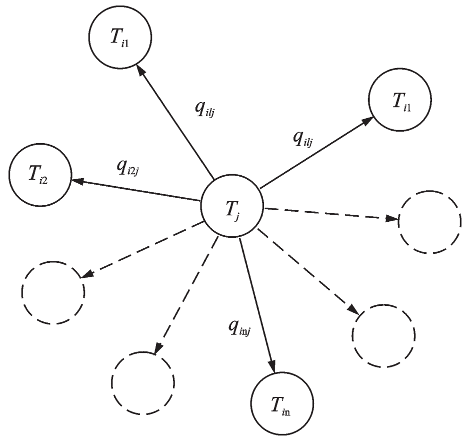

Fig.3 Weighted directed graph Ω

where T_j stands for the task node of receiving information input and T_{in} $(n=1, 2, \cdots, k)$ is one of all task nodes which accept information from T_j. Weighed $w(T_j, T_{in})^j$ of directed arch $(T_j, T_{in})^j$ equals to q_{inj}, which stands for the output information amount exported by T_j to T_{in}.

Based on WDGs Ψ and Ω, any complicated TCM can be combined. According to definition 4, TCM is constituted by Figs.2, 3 as a tuple. Let's set $T_{jn}=T_j$ from Fig.2, and set $T_{in}=T_i$ from Fig.3. In accordance with definition 3, the weight of directed arch (T_j, T_i) in TCM equals to the geometric mean of the weight of directed arch $(T_{jn}, T_i)^i$ in Ψ and the weight of directed arch $(T_j, T_{in})^j$ in Ω.

$$w(T_j,T_i)=r_{ij}=\sqrt{p_{ij}q_{ij}}=\sqrt{p_{ijn}q_{inj}}=\sqrt{w(T_{jn},T_i)^i w(T_j,T_{in})^j} \tag{10}$$

In all, TCM of CEP collaborative development process can be presented by WDG model based on the information relevancy. For instance, there are 20 tasks in the collaborative development process of a radar's phased array antenna: T_1 is the system specification, T_2 antenna specification, T_3 T/R module simulation reporting, T_4 feed network specification, T_5 T/R module specification, T_6 T/R link analysis, T_7 antenna virtual prototype modeling, T_8 system operation analysis, T_9 scan matching simulation, T_{10} antenna simulation reporting, T_{11} virtual system integration analysis, T_{12} small scale simulation, T_{13} RCS simulation, T_{14} amplitude and phase consistency, T_{15} ADS modeling, T_{16} ADS simulation, T_{17} system scheme validation, T_{18} full scale test, T_{19} stakeholder requirement analysis, and T_{20} reliability simulation. The TCM (Fig.4) of this process is constituted by the WDGs Ψ_i and Ω_i ($i=1, 2, \cdots, 20$) of 20 tasks above.

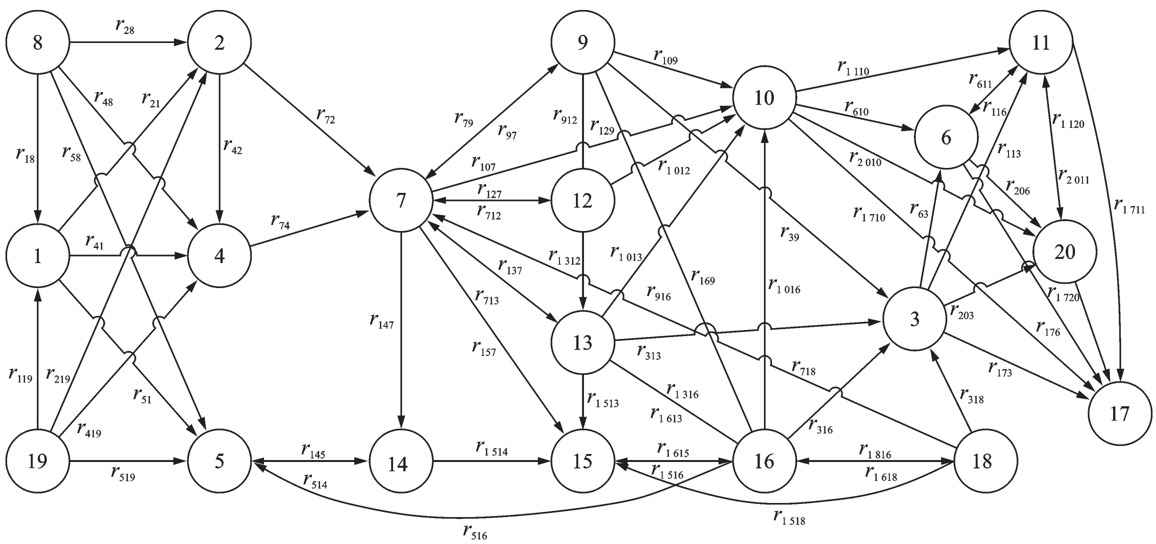

Fig.4 TCM in collaborative development process of radar's phased array antenna

Confronting with such a complicated development process, to improve the development efficiency, it is far from adequate to separate a few tasks for concurrent and serial implementation by merely relying on common methods. If the rest most coupling tasks are combined for implementation, according to concurrent engineering theory, a huge integrated product team (IPT)[18] is necessary. For instance, if tasks T_7, T_9, T_{12}, T_{13}, T_{14}, T_{15} and T_{16} in Fig. 4 are carried out together, then IPT shall include personnel in disciplines of antenna, electromagnetic field, RCS analysis, ADS analysis and so on. As for a research and development institute, these personnel are distributed in different labs, so it's difficult to let them collaboratively work in one IPT at any time. On the contrary, the development efficiency will be lowered. As a result, there is a necessity to decouple coupling task package. Then the decomposed task sub-packages with proper size can implement independently. This solution can greatly shrink the IPT scale needed by implementing tasks, so as to promote the development efficiency.

1.2 TCM presented by DSM

As DSM can make up for the shortage of DG modelling, in order to further analyze TCM presented by DG, it's necessary to present TCM in the form of DSM. There exists a corresponding relation between DG model and DSM. Supposing the form of binary DSM is

$$B=\begin{bmatrix} \ddots & \vdots & ⋰ \\ \cdots & b_{ij} & \cdots \\ ⋰ & \vdots & \ddots \end{bmatrix}_{n\times n} \tag{11}$$

where

$$b_{ij}=\begin{cases} 1 & i=i_1^{(j)}, i_2^{(j)}, \cdots, i_{l_j}^{(j)};\ j=j_1^{(i)}, j_2^{(i)}, \cdots, j_{k_i}^{(i)} \\ 0 & i\neq i_1^{(j)}, i_2^{(j)}, \cdots, i_{l_j}^{(j)};\ j\neq j_1^{(i)}, j_2^{(i)}, \cdots, j_{k_i}^{(i)} \end{cases}$$

then in directed graph model, task node T_i corresponds to row i and column i, directed arch (T_j, T_i) corresponds to the element b_{ij} in $\boldsymbol{B}$. If there exists a directed arch from node T_j to node T_i in DG model, then $b_{ij}=1$. If there is no directed arch from node T_j to node T_i, then $b_{ij}=0$.

Therefore, TCM of CEP in collaborative development process can be presented in the form of Eq.(11).

1.3 Quantitative assignment of TCM

To decouple TCM, Eq.(11) is firstly divided into serial task matrix, concurrent task matrix and coupling task matrix through the partitioning algorithm[19]. To further decouple the coupling task matrix, the binary DSM needs to be quantitative assigned and transformed to numeric DSM. Based on two-way comparison scheme[20]. DSM row/column comparison matrix and then feature vector of comparison matrix are generated. Feature vector of each DSM row's comparison matrix stands for the amount of input information that can be accepted from other sub-tasks by sub-task T_i represented by this row. According to definition 2, $[p_{ij_1^{(i)}}, p_{ij_2^{(i)}}, \cdots, p_{ij_{k_i}^{(i)}}]$ can be used for presenting this feature vector, namely combination of weights of $(T_{jn}, T_i)^i$ on each chain in DG Ψ. The subscript of the element $p_{ij_n^{(i)}}(n=1,2,\cdots,k_i)$ in the feature vector shows that the element is located on the row i and the column $j_n^{(i)}$ in the input information amount matrix below. In the similar way, the feature vector of each DSM column's paired comparison matrix stands for the information amount output to other sub-tasks from sub-task T_j represented by this column. Based on definition 2, $[q_{i_1^{(j)}j}, q_{i_2^{(j)}j}, \cdots, q_{i_{l_j}^{(j)}j}]^{\mathrm{T}}$ can be used for presenting this feature vector, namely combination of weights of $(T_j, T_{in})^j$ on each chain in DG Ω. The subscript of the element $q_{i_n^{(j)}j}(n=1,2,\cdots,l_j)$ in the feature vector means that the element is located on the row $i_n^{(j)}$ and the column j in the output information amount matrix below.

It can be found that there exists a corresponding relation between WDG model and DSM model of TCM. Based on $[p_{ij_1^{(i)}}, p_{ij_2^{(i)}}, \cdots, p_{ij_{k_i}^{(i)}}]$ as the row of matrix, input information amount matrix $\boldsymbol{P}$ of each subtask in coupling task package can be formed. The output information amount matrix $\boldsymbol{Q}$ of each subtask in coupling task package can be formed on the basis of $[q_{i_1^{(j)}j}, q_{i_2^{(j)}j}, \cdots, q_{i_{l_j}^{(j)}j}]^{\mathrm{T}}$ as the matrix column. Elements (not 0) of matrices $\boldsymbol{P}$ and $\boldsymbol{Q}$ can reveal that a common directed edge exists between task nodes, so elements (not 0) of two matrices are one-to-one corresponding. In line with Definition 3, the geometric mean of relevant elements p_{ij} and q_{ij} in matrices $\boldsymbol{P}$ and $\boldsymbol{Q}$ equals to relevancy r_{ij} of T_i and T_j and the matrix $\boldsymbol{R}$ is a relevancy matrix of coupling task package.

$$\boldsymbol{R}=\begin{bmatrix} r_{11} & \cdots & r_{1j} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ r_{i1} & \cdots & r_{ij} & \cdots & r_{in} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nj} & \cdots & r_{nn} \end{bmatrix}=$$

$$\begin{bmatrix} 0 & \cdots & \sqrt{p_{1j}q_{1j}} & \cdots & \sqrt{p_{1n}q_{1n}} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \sqrt{p_{i1}q_{i1}} & \cdots & 0 & \cdots & \sqrt{p_{in}q_{in}} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \sqrt{p_{n1}q_{n1}} & \cdots & \sqrt{p_{nj}q_{nj}} & \cdots & 0 \end{bmatrix} \tag{12}$$

At this point, the binary DSM of TCM is transformed into a numeric DSM by means of quantifying the information relevancy between the coupled tasks, and the weight assignment of the corresponding WDG model is completed.

1.4 Interactivity matrix of coupling task package

In the process of collaboratively developing CEP, if tasks T_i and T_j are in coupling relationship, the information delivery between them is two-way. As a result, to completely present the information delivery relation between T_i and T_j, the concept of interactivity shall be introduced.

Definition 5 The magnitude of mutual information interaction between tasks T_i and T_j is called as interactivity, which can be denoted as

$$i_{ij}=\alpha r_{ij}+\beta r_{ji} \tag{13}$$

where α and β are the weights of r_{ij} and r_{ji}, respectively. When $i=j$, $i_{ij}=0$.

According to the definition of interactivity, if tasks T_i and T_j are serial (information delivered from T_j to T_i), then $i_{ij}=\alpha r_{ij}$; if T_i and T_j are concurrent, then $i_{ij}=0$; if they are coupled, suppose $\alpha=\beta=0.5$, then

$$i_{ij}=\frac{r_{ij}+r_{ji}}{2} \tag{14}$$

Based on definition 5, the interactivity matrix $\boldsymbol{I}$ of coupling task package can be obtained from relevancy matrix $\boldsymbol{R}$.

$$\boldsymbol{I}=\begin{bmatrix} i_{11} & \cdots & i_{1i} & \cdots & i_{1n} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ i_{i1} & \cdots & i_{ii} & \cdots & i_{in} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ i_{n1} & \cdots & i_{ni} & \cdots & i_{nn} \end{bmatrix}=$$

$$\begin{bmatrix} 0 & \cdots & \frac{r_{1i}+r_{i1}}{2} & \cdots & \frac{r_{1n}+r_{n1}}{2} \\ \vdots & \ddots & \vdots & \iddots & \vdots \\ \frac{r_{1i}+r_{i1}}{2} & \cdots & 0 & \cdots & \frac{r_{in}+r_{ni}}{2} \\ \vdots & \iddots & \vdots & \ddots & \vdots \\ \frac{r_{1n}+r_{n1}}{2} & \cdots & \frac{r_{in}+r_{ni}}{2} & \cdots & 0 \end{bmatrix} \tag{15}$$

It is obviously that matrix $\boldsymbol{I}$ is symmetrical, which has made coupling task package TCM transform from binary DSM to numeric DSM.

2 Decoupling Method Based on Improved Genetic Algorithm

To decouple TCM presented by Eq. (15), the thesis has come up with a multi-goal decoupling method based on the improved genetic algorithm. First of all, based on related aggregation degree and connection degree, individual of the initial population will be sorted and screened. Then, a new population will be intersected and vary, eventually, decoupling program will be obtained.

2.1 Confirmation of the goal function of coupling task package decoupling

Supposing that coupling task package can be decoupled into K task sub-packages, the affiliation between subtasks in coupling task package and K task sub-packages can be presented as affiliation matrix $\boldsymbol{M}$.

$$\boldsymbol{M}=[m_{ik}]_{n\times K}=[\boldsymbol{M}_k]_K \tag{16}$$

where $m_{ik}=\begin{cases}1 & T_i\in \text{sub-package } k \\ 0 & T_i\notin \text{sub-package } k\end{cases}$, $\boldsymbol{M}_k$ is the affiliation vector between subtask and task sub-package k.

Based on the affiliation matrix, aggregation degree and connection degree of coupling task package can be acquired.

Definition 6 Aggregation degree of task sub-package stands for the closeness of subtasks contained in one task sub-package, and is measured by the average interactivity among subtasks of task sub-package k.

$$A_k=\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} i_{ij}m_{ik}m_{jk}\Big/\sum_{i=1}^{n-1}\sum_{j=i+1}^{n} m_{ik}m_{jk} \tag{17}$$

where i_{ij} is the interactivity between task i and task j.

The total aggregation degree of coupling task package is the average aggregation degree of K task sub-packages.

$$A_{\text{total}}=\left[\sum_{k=1}^{K}\boldsymbol{M}_k^{\mathrm{T}}\boldsymbol{I}\boldsymbol{M}_k/D_k(D_k-1)\right]\Big/K \tag{18}$$

where D_k is the amount of subtasks in task sub-package k.

Definition 7 Task sub-package connection degree presents the closeness between each task sub-package contained in coupling task package, and is measured by the average interactivity between subtasks which are respectively belonged to sub-packages a and b.

$$C_{ab}=\left(\sum_{i=1}^{n}\sum_{j=1}^{n} i_{ij}m_{ia}m_{jb}\right)\Big/(D_a\cdot D_b) \tag{19}$$

where D_a and D_b are subtasks amounts of task sub-packages a and b, respectively.

The total connection degree of coupling task package is the average value of paired connection degrees between task sub-packages.

$$C_{\text{total}}=\left\{\left[\left(\frac{\boldsymbol{M}_k}{\boldsymbol{D}_k}\right)^{\mathrm{T}}\right]_{1\times K}[\boldsymbol{I}]_K\left[\left(\frac{\boldsymbol{M}_k}{\boldsymbol{D}_k}\right)\right]_{K\times 1}-n\right\}\Big/[K(K-1)] \tag{20}$$

The decoupling goal of coupling task package is to divide the package into several task sub-packages, so as to make the total aggregation degree of task package the maximum and total connection degree the minimum. This is a typical multi-goal optimization issue. Because A_{total} and C_{total} have the same dimensions and magnitude orders, the goal function of coupling task package is set as

$$\min f(A_{\text{total}}, C_{\text{total}}) = -A_{\text{total}} + C_{\text{total}} \tag{21}$$

$$\text{s.t.} \sum_{k=1}^{K} m_{ik} = 1 \quad i = 1, 2, \cdots, n \tag{22}$$

$$\sum_{i=1}^{n} m_{ik} = D_k \quad k = 1, 2, \cdots, K \tag{23}$$

$$\sum_{k=1}^{K} D_k = n \quad 2 \leqslant K \leqslant n \tag{24}$$

2.2 Improved genetic algorithm

The genetic algorithm has high search efficiency and is widely used in multi-objective optimization problems[21]. The improved genetic algorithm[22-23] is effectively applied to the process planning problem solving. The thesis designs an improved genetic algorithm to solve Eq.(21). The algorithm framework is shown in Fig.5.

Step 1 Setting up the initial population. Different individuals of the initial population stand for different decoupling methods of coupling task package. Various decoupling methods divide coupling task package into several task sub-packages (2 to n). It is supposed that the occurrence probabilities of decoupling methods related to each amount of task sub-packages are equal.

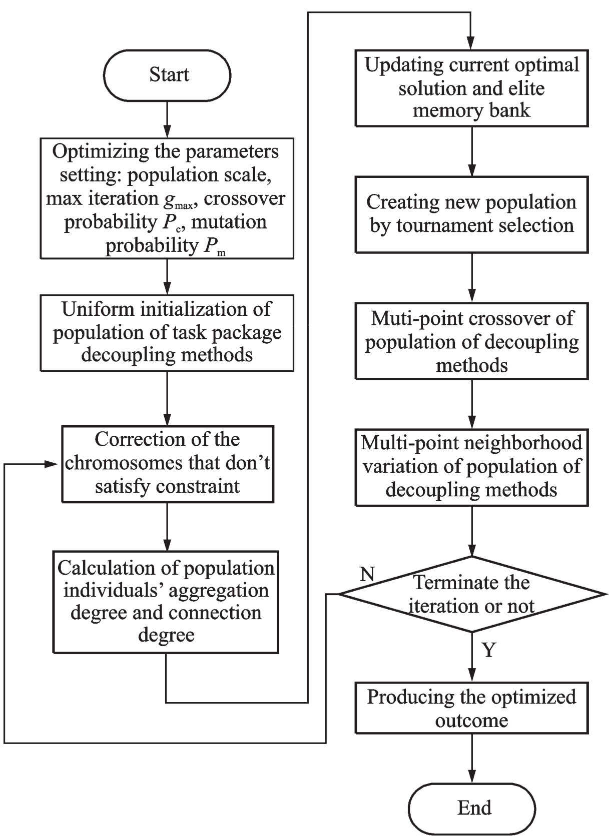

Fig.5 Framework of the improved genetic algorithm

Step 2 Encoding chromosome. Chromosome encode is generated based on affiliation matrix $\boldsymbol{M}$ which presents decoupling method. The encoding length is n. Each code bit assigns a value ranging from 1 to n, and is decided by the number of sub-package with the task which the code bit respectively represents. By calculating the total aggregation degree and connection degree of related coupling task package, the individual adaptive value can be acquired.

Step 3 Tournament selection. A random amount of chromosomes have been selected to participate in the tournament. Individuals are assessed by their adaptive value, and the current optimum individual is added in the evolution population. The evolution population establishment will be completed after several selections.

Step 4 Multi-point crossover. Several locations in two parent chromosomes are randomly selected. Thereafter, related task sub-packages' numbers are exchanged.

Step 5 Multi-point neighborhood variation. Several locations in one parent chromosome are randomly selected, and a new arrangement will be acquired in the neighborhood of related task sub-packages' numbers arrangement.

Step 6 An optimized outcome will be produced as the maximum iteration has been reached, otherwise, the algorithm will skip to step 2.

3 Case Study

Next, TCM in collaborative development process of radar's phased array antenna is decoupled in Fig.4. This TCM can be presented in binary DSM in Fig.6, and then the partitioning algorithm can be used for dividing DSM in Fig. 6 into partitioned DSM as shown in Fig.7. T_8 and T_{19}, and T_{10} and T_3 are concurrent tasks. T_1, T_2 and T_4 are serial tasks. Task package $\{T_7, T_9, T_{12}, T_{13}, T_5, T_{14}, T_{15}, T_{16}, T_{18}\}$

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
System specification	1	×							1											1	
Antenna specification	2	1	×						1											1	
T/R module simulation reporting	3			×						1				1			1		1		
Feed network specification	4	1	1		×				1											1	
T/R module specification	5	1				×			1						1		1			1	
T/R link analysis	6			1			×				1	1									1
Antenna virtual prototype modeling	7		1		1			×		1			1	1					1		
System operation analysis	8								×												
Scan matching simulation	9							1		×			1				1				
Antenna simulation reporting	10							1		1	×		1	1			1				
Virtual system integration analysis	11			1			1				1	×									1
Small scale simulation	12							1		1			×								
RCS simulation	13							1					1	×			1				
Amplitude and phase consistency	14					1		1							×						
ADS modeling	15							1						1	1	×	1		1		
ADS simulation	16									1				1		1	×		1		
System scheme validation	17			1			1				1	1						×			1
Full scale test	18																1		×		
Stakeholder requirement analysis	19																			×	
Reliability simulation	20			1			1				1	1									×

Fig.6 Unpatitioned DSM of collaborative development process of phased array anntenna

		8	19	1	2	4	7	9	12	13	5	14	15	16	18	10	3	11	6	20	17
System operation analysis	8	×																			
Stakeholder requirement analysis	19		×																		
System specification	1	1	1	×																	
Antenna specification	2	1	1	1	×																
Feed network specification	4	1	1	1	1	×															
Antenna virtual prototype modeling	7				1	1	×	1	1	1					1						
Scan matching simulation	9						1	×	1					1							
Small scale simulation	12						1	1	×												
RCS simulation	13						1		1	×				1							
T/R module specification	5	1	1	1							×	1		1							
Amplitude and phase consistency	14						1				1	×									
ADS modeling	15						1			1		1	×	1	1						
ADS simulation	16							1		1			1	×	1						
Full scale test	18													1	×						
Antenna simulation reporting	10						1	1	1	1				1		×					
T/R module simulation reporting	3							1		1				1	1		×				
Virtual system integration analysis	11															1	1	×	1	1	
T/R link analysis	6															1	1	1	×	1	
Reliability simulation	20															1	1	1	1	×	
System scheme validation	17															1	1	1	1	1	×

Fig.7 Patitioned DSM of collaborative development process of phased array anntenna

and $\{T_{11}, T_6, T_{20}\}$ are coupling tasks.

Task package $\{T_7, T_9, T_{12}, T_{13}, T_5, T_{14}, T_{15}, T_{16}, T_{18}\}$ is selected for decoupling. By transforming the TCM of radar's phased array antenna collaborative development coupling task package TCM from binary DSM into numeric DSM, interactivity matrix $\boldsymbol{I}$ of coupling task package has been attained.

$$
I=\begin{array}{cc}
\begin{array}{ccccccccc} 7 & 9 & 12 & 13 & 5 & 14 & 15 & 16 & 18 \end{array} & \\
\left[\begin{array}{ccccccccc}
0 & 0.288\,0 & 0.455\,3 & 0.440\,3 & 0 & 0.031\,2 & 0.059\,8 & 0 & 0.037\,8 \\
0.288\,0 & 0 & 0.304\,6 & 0 & 0 & 0 & 0 & 0.090\,4 & 0 \\
0.455\,3 & 0.304\,6 & 0 & 0.221\,0 & 0 & 0 & 0 & 0 & 0 \\
0.440\,3 & 0 & 0.221\,0 & 0 & 0 & 0 & 0.075\,2 & 0.150\,2 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.648\,2 & 0 & 0.0700 & 0 \\
0.031\,2 & 0 & 0 & 0 & 0.648\,2 & 0 & 0.3311 & 0 & 0 \\
0.059\,8 & 0 & 0 & 0.075\,2 & 0 & 0.331\,1 & 0 & 0.531\,2 & 0.062\,4 \\
0 & 0.090\,4 & 0 & 0.150\,2 & 0.070\,0 & 0 & 0.531\,2 & 0 & 0.243\,9 \\
0.037\,8 & 0 & 0 & 0 & 0 & 0 & 0.062\,4 & 0.243\,9 & 0
\end{array}\right] & \begin{array}{c} 7 \\ 9 \\ 12 \\ 13 \\ 5 \\ 14 \\ 15 \\ 16 \\ 18 \end{array}
\end{array}
$$

In accordance with the goal function in Eq.(21), I can be decoupled by taking use of the improved genetic algorithm. Algorithm parameters are set as: the initial population scale is 200, the maximum iteration is 100, the crossover operator P_c=0.8 and mutation operator P_m=0.01. The final decoupling program is to decouple task package $\{T_7, T_9, T_{12}, T_{13}, T_5, T_{14}, T_{15}, T_{16}, T_{18}\}$ into 3 task sub-packages, $\{T_7, T_9, T_{12}, T_{13}, T_{18}\}$, $\{T_5, T_{14}\}$ and $\{T_{15}, T_{16}\}$. And aggregation degree $A_{\text{total}} = 0.451\,4$, connection degree $C_{\text{total}} = 0.057\,2$. After several times of calculation, the convergence curve is obtained in Fig.8. It indicates that the objective function reaches the minimum value when the scheme is selected. The scheme is best.

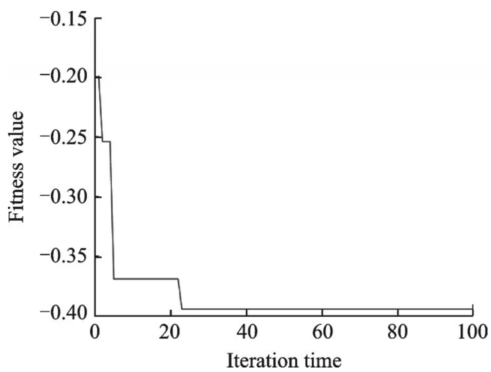

Fig.8 Evolution process convergence curve of collaborative development task package decoupling

Comparing the task packages before and after optimization, we can find that there are large loop design iterations and more feedback for the task packages before decoupling, and the large loop is decomposed into three small loops with less feedback after decoupling. In a project of radar's phased array antenna development implemented by one research institute, the traditional method is to set up a large IPT consisted of personnel from several labs like antenna, array plane, TR unit, and structure for collaboration. After the coupling method in this thesis has been adopted, coupling task package is divided into smaller sub-packages, and the large IPT can take the place of smaller ones. Hence the tasks are carried out more flexibly. The results show that the method is effective for the task planning of radar's phased array antenna development project.

4 Conclusions

In the collaborative process of CEP, there exists complicated information coupling relation among subtasks of development task package. By adopting WDG and numeric DSM, the thesis has modelled and decoupled the task package in collaborative development process. Firstly, TCM of collaborative development process has been set up. The information interactivity between coupled tasks is quantitatively assigned by two-way comparison scheme. So the physical significance of corresponding relation between WDG and numeric DSM has been confirmed. Then, based on the improved genetic algorithm, the thesis has come up with multi-goal decoupling method for coupling task package, transformed decoupling of coupling task package into typical multi-goal optimization issue, and then solved the interactivity matrix of task package. Lastly, based on the example of decoupling TCM of radar's phased array antenna in collaborative development process, this decoupling method has been verified to be effective.

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