Research on the Influence of Resource Allocation Uncertainty on Parallel Coupling Iteration Time

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Abstract. Aiming at the problem that the uncertainty of resource allocation can lead to the increase of the parallel iteration time of the coupled task set, a parallel iteration time optimization model under the uncertainty of resource allocation was constructed based on the analysis of the resource allocation uncertainty and iteration time model in the parallel iteration. Then the analytic hierarchy process (AHP) was introduced, and by determining the AHP model and the resource allocation matrix, an improved parallel iteration time optimization model under the uncertain resource allocation was constructed. Combined with an example of product development process, application research was carried out by applying the MATLAB software, thereby verifying that the improved optimization model can reduce the parallel iteration time of the coupled task set under uncertain resource allocation. This research provides a reference for optimizing resource allocation and reducing time in product design and development.

Keywords: resource allocation, uncertainty, coupled task set, parallel iteration time, analytic hierarchy process (AHP).

1. Introduction

As a complex creative activity, product development needs to consider many uncertain factors such as funding, equipment, and conflicts and collaborations among multiple departments. These uncertain factors can be divided into external environmental factors and internal interaction factors of the project. Among them, external environmental factors include changes in the personal preferences of corporate customers, changes in market purchasing power, sudden personnel movements and natural disasters, restrictions on technical bottlenecks, and the control objectives and uncertainty of planned duration caused by the uncertainty of management decision-making behavior, etc. And the internal interaction factors of the project include the information on the progress of upstream and downstream design tasks, the resource consumption information of each task configuration, and the uncertainty of interdisciplinary technical information during the product design development process, uncertainty of design task execution priority and uncertainty of resource allocation. The above factors will lead to uncertainty in product development. Compared with external environmental factors, internal interaction factors of the project are easy to coordinate and manage, and have certain controllability [1].
Resources are important factors influencing the product development process. Among them, human resources, processing equipment, etc. are renewable and can be added, and rational allocation of them can effectively shorten the project completion time. However, resource allocation methods often have large uncertainties, which are caused by the uncertainty of task execution duration and the uncertainty of task output branches. In the case of limited resources, tasks with too few resources could not be executed smoothly, and other tasks were associated with the task, which led to the iterative rework of other tasks on the task. For the parallel development process, the task with the longest execution time ultimately determines the completion time of the entire development process. Tasks with under-allocated resources increase the task execution time due to iterative rework, which eventually leads to a lengthy development cycle. It can be seen that allocating resources according to experience is an important cause of uncertainty in resource allocation. This approach to resource allocation prolongs the completion time of the entire development process by causing iterative rework between tasks. At present, many scholars at home and abroad have studied the uncertainty of resource allocation in the internal interaction factors of the project and achieved corresponding results. For example: Xiao Renbin et al. proposed a solution model based on resource equilibrium strategy, which solved the problem of resource idleness caused by uneven resource allocation [2]; Michele Lombardi et al. applied interdisciplinary survey methods to optimize resource scheduling and Allocation problem [3]; Chen Weiming et al. established a coupled set solution model based on mixed iterations in a dynamic environment, and analyzed the impact of resource allocation uncertainty on product development cycles and costs [4]; Li Xiaoya et al. proposed an extra resource allocation model based on data envelopment analysis method. This model makes resource allocation more objective by comprehensively considering two factors: scale and efficiency [5]; Xiang Qian et al. proposed an improved dynamic differential evolution parameter control and two-way scheduling algorithm for the optimization of resource-constrained project portfolio optimization, which improved the algorithm's convergence and optimization capabilities [6]; Karine Altisen et al. proposed a resource allocation algorithm to solve the problem of parallel resource allocation [7].

Based on the analysis of the parallel iteration time model, this paper first builds a parallel iteration time optimization model under the condition of uncertain resource allocation. Then by introducing the analytic hierarchy process (AHP), an improved model for parallel iteration time optimization under uncertain resource allocation conditions is obtained. Finally, combined with product development process examples, the effects of uncertain resource allocation conditions on the parallel coupling iteration time under the two models are compared and analyzed to verify the effectiveness of the improved optimization model.

2. Determination of parallel iteration time model

For the product design and development process with n tasks, according to literature [8-9], the total workload model of the parallel iteratively coupled task set is:

\[ U = WS \left( \lim_{M \to \infty} \sum_{m=0}^{M} A^m \right) S^{-1} u_0 \]

where: \( U \) is the total workload matrix for all tasks(\( n \times 1 \) order) ; \( W \) is the diagonal matrix of the workload matrix corresponding to each task(\( n \times n \) order) ; \( M \) represents the total number of iterations of the coupled set; \( m \) is the current number of iterations of the coupled set; \( A \) is the eigenvalue matrix of the Work Transition Matrix (WTM) \( A(1 \times n \) order \) ; \( S \) is the eigenvector matrix of matrix \( A(n \times 1 \) order \) ; \( u_0 \) is the \( n \times 1 \) dimensional initial working vector whose elements are all numbers 1.

When the maximum eigenvalue \( \lambda_{\max} < 1 \) of matrix \( A \), the parallel coupling iterative process is convergent [9], then there is \( \lim_{M \to \infty} \left( \sum_{m=0}^{M} A^m \right) = (I - A)^{-1} \), Bring into (1) and get:

\[ U = WS \left( I - A \right)^{-1} S^{-1} u_0 \]

(2)
In the formula: \( I \) is the identity matrix.

In the coupled set parallel iterative model, the workload of a task is not simply expressed by the completion time of the task. The workload takes into account the time \( T \) and resource \( R \) used for product development. The workload of the task can be expressed as the product of the two [10], namely:

\[
U = RT
\]

In the process of product design and development, according to past experience, we can know that the workload of each design task is constant. From (3), we can know that the completion time of each task is different when the source quantity is different. To complete a design task, more than one type of human resource is usually required. Assume that a product design and development requires \( q \)-type human resources, and its tasks are performed in parallel. Under the execution of tasks that require \( k \)-type human resources, from equations (2) and (3), the parallel iteration time of the entire task group is:

\[
T^{(k)} = \left[ R^{(k)} \right]^{-1} U = \left[ R^{(k)} \right]^{-1} WS (I - A)^{-1} S^{-1} u_0
\]

In the formula: \( T^{(k)} \) is an \( n \)-dimensional column vector, which is \( T^{(k)} = (t_1^{(k)}, t_2^{(k)}, ..., t_n^{(k)})^T \), \( k = 1, 2, ..., q \); Its element \( t_j^{(k)} \) represents the time consumed by task \( j \) under the execution of the \( k \)-type resource; Resource Allocation Matrix \( R^{(k)} = \text{diag}(t_1^{(k)}, t_2^{(k)}, ..., t_n^{(k)}) \), the diagonal element \( r_j^{(k)} \) represents the amount of resources allocated to the \( j \) task by the \( k \)-type resource.

Equation (4) also shows that \( T^{(k)} \) is a function of \( R^{(k)} \), that is:

\[
T^{(k)} = f(R^{(k)})
\]

The number of types of human resources required by the coupled task set is \( q \), and the entire parallel development process is a task group composed of \( n \) tasks. The type of human resources with the longest execution time ultimately determines the completion time of the entire development process, then the entire parallel development the completion time of the process is:

\[
T = \max \left( T^{(k)} \right)^T
\]

where \( \left( f(R^{(k)}) \right)^T \) is the transpose of \( f(R^{(k)}) \).

3. Hierarchical model of resource allocation and determination of resource allocation matrix

The purpose of resource allocation in coupled tasks is to reasonably allocate various types of resources to tasks, so set the allocated resources as the target layer; the principle of resource allocation is to allocate resources according to the degree of task's demand for resources, so set each task is the criterion layer; because there are multiple resources to choose from for each task, each resource is set as solution layer. Aiming at the resource allocation problem, using the Analytic Hierarchy Process(AHP), with resource allocation as the target layer, tasks as the criterion layer, and various resources required by the task as the solution layer, a hierarchical resource allocation model for the coupled task set is shown in Figure 1.
As can be seen from Figure 1, the strategy for resource allocation is to allocate each type of resource to multiple tasks one by one, rather than simultaneously assigning multiple types of resources to multiple tasks at the same time, that is, the relationship between resources and tasks is a one-to-many relationship, and not a many-to-many relationship. Then in this process, resources and resources can be regarded as relatively isolated. Each time a certain type of resource is allocated, the impact of other types of resources can be ignored, that is, there is no need to consider whether there is a problem of different importance between resources. What needs to be considered is the problem of different demand among multiple tasks. Therefore, in the process of resource allocation, the weight ratio of each task's relative demand for each type of resource must be compared.

The relative demand for the same resource by different tasks in a coupled task set is generally different. In order to distinguish and quantify the relative requirements of different tasks for the same resource, a numerical scale 1-9 is used to indicate the weight ratio of the relative requirements of the two tasks to the same resource [12]. The specific meaning is shown in Table 1.

### Table 1. The weight ratio of the relative requirements of the two tasks to the same resource.

| Weight ratio | meaning                                      |
|--------------|----------------------------------------------|
| 1            | Two tasks require the same amount of resources|
| 3            | Two tasks require the same resource one slightly more than the other |
| 5            | Two tasks require the same resource more clearly than the other |
| 7            | Two tasks require the same resource more strongly than the other |
| 9            | Two tasks require the same resource more severely than the other |
| 2,4,6,8      | The median of the above two adjacent demand levels |
| reciprocal   | If task $i$ is compared to task $j$ by $a_{ij}$, then task $j$ is compared with task $i$ by $a_{ji}=1/a_{ij}$ |

In Table 1, the greater the value of the weight ratio, the greater the difference in the degree of demand for the same resource between the two tasks being compared, that is, the task being compared requires more such resources than the task being compared. The weight ratio is "reciprocal", which indicates that the two tasks are compared in turn. For example, task A requires 3 times the resource k as task B. Then, in turn, task B requires resource k as $1/3$.

In order to avoid the influence of personal subjectivity on the demand comparison process, the expert group evaluation method is adopted [13]. For the same resource, multiple experts compare each task in the coupled task set according to the degree of demand. The comparison results are expressed by the corresponding weight ratios in Table 1, and the multiple weight ratios of each two tasks are respectively expressed. Perform a weighted average. If the weighted average value cannot be represented in Table 1, the value closest to the value in the table is taken, and then the weighted average weight ratio values are arranged according to a certain rule to form a resource allocation matrix. For a coupled design task set consisting of $n$ tasks, the number of types of resource requirements is $q$, and resources of $q$ class need to be allocated to $n$ tasks. Matrix $D^{(k)}$ is used to represent the allocation matrix of resource $k$. According to the model shown in Figure 1 and the weight ratio shown in Table 1, matrix $D^{(k)}$ is expressed as follows:
In the formula: Matrix $D^{(k)}$ is an $n$-dimensional square matrix with the number of tasks equal to the number of tasks in the coupled task set, and its elements represent the weight ratio obtained by comparing each task's demand for resource $k$ in the coupled task set. For example, in the resource $k$, $d_{ij}^{(k)}$ represents the weight ratio obtained by comparing the demand degree of task $i$ with the demand degree of task $j$; The diagonal elements of the matrix $D^{(k)}$ represent the weight ratios obtained from the self-comparison of each task for resource $k$, so they are all 1; Taking the main diagonal element as the boundary, the upper triangle element and the lower triangle element are mutually reciprocal, that is, there is $d_{i}^{(k)} \times d_{j}^{(k)} = 1$.

4. Construction of parallel iterative time optimization model

4.1. Model construction

Under the condition of uncertain resource allocation, the maximum amount of resources allocated by the manager to each task is the average value of the total resources, so that each element in the resource amount matrix has its own value range.

If the total resource amount of the $k$-type resource that can be provided in the product design process is $r^{(k)}$, then the resource amount obtained by $n$ design tasks is between 0 and $r^{(k)}/n$, that is, the parallel iteration time optimization model under the condition of uncertain resource allocation resource constraints are:

$$0 < r^{(k)} = \frac{1}{n} r^{(k)} j = 1, 2, \ldots, n$$

In the process of parallel product development, the tasks are in a parallel iterative relationship. The sub-task with the longest execution time determines the completion time of the entire task team. Therefore, the optimization model should be coupled to the task with the longest central execution time. The shortest completion time of the sub-task is the goal. The objective function of the parallel iteration time optimization model under the condition of uncertain resource allocation is:

$$F = \min \left( \max \left( f(R^{(k)}) \right)^T \right)$$

According to the above analysis and equations (7) and (8), a parallel iteration time optimization model can be obtained under the condition of uncertain resource allocation:

$$f(R^{(k)}) = \left[ (R^{(k)})^T \right]^T WS (I - A)^T S^{-1} u_0$$

$$\begin{align*}
object: F &= \min \left( \max \left( f(R^{(k)}) \right)^T \right) \\
s.t.: 0 < r^{(k)} = \frac{1}{n} r^{(k)}
\end{align*}$$

4.2. Model improvement

If the number of tasks in the coupled task set is $n$, it requires $q$-type resources. For each element $r_j$ in the resource allocation matrix $D$, the maximum amount of $q$-type resources that $n$ tasks should allocate
is obtained through the analytic hierarchy process, so as to determine the value range of \( r_j \). When \( r_j \) has its own value range, its set constitutes the resource constraints of the parallel iteration time optimization model. The method of determining the resource allocation weight based on the analytic hierarchy process [13], the specific process of determining the resource constraint conditions can be shown in Figure 2.

Figure 2. Flow chart of analytic hierarchy process to determine resource constraints.

As can be seen from Figure 2, in the determination of the weight ratio of the demand for the same resource for each two tasks, because the maximum demand for resources is compared by task, the demand for a certain type of resource is finally obtained as Maximum resource requirements. In the process of resource allocation, it is usually based on the principle of completing as many tasks as possible with as few resources as possible, that is, without causing waste of resources. Therefore, each element in the resource allocation matrix \( D \) obtained according to Figure 2 is not an accurate value. That is, there is a value range, which should be less than or equal to the maximum resource requirement. According to the above analysis, during the execution of the \( k \)-th resource, the constraints of the parallel iteration time optimization model become:

\[
0 < r_j^{(k)} \leq \max \left\{ r_j^{(k)} \right\} \\
0 < \sum_{j=1}^{n} r_j^{(k)} \leq r^{(k)}, \quad (k = 1, 2, \cdots, q; j = 1, 2, \cdots, n)
\]  

(10)

In the formula: \( \max \left\{ r_j^{(k)} \right\} \) represents the maximum amount of the \( k \)-th resource allocated to task \( j \) obtained by using the analytic hierarchy process, so task \( j \) should be allocated the number of resources \( k \) and \( r_j^{(k)} \) should not be greater than \( \max \left\{ r_j^{(k)} \right\} \); \( r^{(k)} \) represents the maximum amount of resources \( k \) provided, so the sum of the resources allocated to each task should not be greater than \( r^{(k)} \), then the improved parallel iteration time optimization model under uncertain resource allocation conditions is:

\[
\begin{align*}
\text{find : } & f(R^{(k)}) = \left[ (R^{(k)})^T \right]^T WS (I - A)^T S^T u_q \\
\text{object : } & F = \min \left\{ \max \left\{ f(R^{(k)}) \right\}^T \right\} \\
\text{s.t.: } & 0 < r_j^{(k)} \leq \max \left\{ r_j^{(k)} \right\}, 0 < \sum_{j=1}^{n} r_j^{(k)} \leq r^{(k)}
\end{align*}
\]  

(11)

5. Case analysis
Taking the development process of a portal crane luffing system [14] as an example, this design project includes multiple design tasks. In order to study the impact of the uncertainty of resource allocation on the parallel iteration time, the elephant trunk design (D1), boom design (D2), luffing motor design (D3), counterweight design (D4), luffing transmission scheme design (D5), and other design task are selected. The simplified design task coupling information is shown in Figure 3.
Figure 3. Coupling information of crane luffing system development process.

From Figure 3, the task rework matrix $A$ and the initial workload matrix $W$ are:

$$
A = \begin{bmatrix}
0 & 0.3 & 0 & 0 & 0 \\
0.2 & 0 & 0 & 0 & 0.1 \\
0 & 0.3 & 0 & 0 & 0.3 \\
0 & 0.2 & 0.3 & 0 & 0.1 \\
0 & 0 & 0.2 & 0.2 & 0
\end{bmatrix}
$$

(12)

$$
W = \text{diag}(11,13,14,22,10)
$$

(13)

For the coupled task set composed of these five tasks, as the design task involves multiple disciplines, three human resources are required: mechanical engineer $r^{(1)}$, mechatronic engineer $r^{(2)}$ and structural engineer $r^{(3)}$. Only having those resources that tasks can be executed smoothly in the coupled task.

Now, the maximum supply of these three resources is set as $r^{(1)} = 15$ people, $r^{(2)} = 20$ people, $r^{(3)} = 10$ people, according to (8), (11), (12), and the application of MATLAB software calculation can obtain the optimization results of the parallel iterative working time $T$ under the condition of uncertain resource allocation, as shown in Table 2.

Table 2. Convergence values of optimal $T$ under uncertain resource allocation.

| The resource type | Mechanical engineer | Mechatronic engineer | Structural engineer |
|-------------------|----------------------|----------------------|---------------------|
| Time $T$ convergence value | 16.4972 | 12.3724 | 24.7449 |

Because each resource uses parallel execution when performing each task, the completion time of the resource with the longest execution time is the final completion time of the entire development process, that is, the completion time of the entire development process is 24.7449 days.

In order to study the impact of the uncertainty of resource allocation on the parallel iteration time, according to the flow chart shown in Figure 2, using the analytic hierarchy process to establish a resource allocation hierarchy model for these three resources as follows:
Combined with the expert group evaluation method in literature [12], five experts will compare each two task to set according to the task maximum demand for each of the three types of resources, and determine the maximum demand for the three resources by the five tasks Weight ratio. The distribution matrix $D^{(1)}$ of mechanical engineer resources, the distribution matrix $D^{(2)}$ of mechanical and electrical engineers resources, and the distribution matrix $D^{(3)}$ of structural engineer resources are obtained. The three resource distribution matrices are as follows (the values in the matrix are the ratios of the degree of demand):

$$
\begin{align*}
D^{(1)} &= \begin{bmatrix}
1 & 1 & 1 & 8 & 7 & 9 \\
1 & 1 & 8 & 6 & 8 \\
1/7 & 1/6 & 7 & 1 & 7 \\
1/9 & 1/8 & 1/2 & 1/7 & 1
\end{bmatrix}, \\
D^{(2)} &= \begin{bmatrix}
1 & 1 & 1 & 8 & 1/5 \\
1 & 1 & 1/7 & 1/3 \\
8 & 7 & 1 & 6 & 2 \\
5 & 3 & 1 & 6 & 1 \\
7 & 6 & 1 & 2 & 1/8
\end{bmatrix}, \\
D^{(3)} &= \begin{bmatrix}
1 & 1 & 1/6 & 1/5 & 8 \\
1 & 1 & 1/3 & 1/2 & 9 \\
6 & 3 & 1 & 4 & 5 \\
5 & 2 & 1/4 & 1 & 7 \\
1/8 & 1/9 & 1/5 & 1/7 & 1
\end{bmatrix}
\end{align*}
$$

By solving the matrices $D^{(1)}$, $D^{(2)}$ and $D^{(3)}$, respectively, the corresponding maximum features [13] $\lambda_{\text{max}}^{(1)} = 5.3460$, $\lambda_{\text{max}}^{(2)} = 5.3210$ and $\lambda_{\text{max}}^{(3)} = 5.4142$ are obtained, and the corresponding feature vectors are:

$$
\begin{align*}
X^{(1)} &= (0.3013,0.4653,0.3416,0.7657,0.4262)^T, \\
X^{(2)} &= (0.1913,0.2191,0.3846,0.2804,0.1162)^T, \\
X^{(3)} &= (0.1322,0.2798,0.4504,0.5347,0.2061)^T.
\end{align*}
$$

$X^{(1)}$, $X^{(2)}$, $X^{(3)}$ were normalized, getting the weight distribution vectors of three resources: $X^{(1)} = (0.1310,0.2023,0.1485,0.3329,0.1853)^T$, $X^{(2)} = (0.1594,0.1826,0.3205,0.2337,0.0968)^T$, $X^{(3)} = (0.0806,0.1749,0.2815,0.3342,0.1288)^T$.

According to the criterion for determining the consistency of the resource allocation matrix in literature [15], the consistency ratio value of the resource allocation matrix constructed above is within an acceptable range, so there is no need to readjust the weight ratio.

Because the allocated resources are human resources (units are people), the amount of resources allocated according to the above weight vector should be taken as an integer, that is, the five tasks of the coupled task set should be allocated to the three resources of mechanical engineer, mechanical, mechatronic engineer and structural engineer the maximum resource vectors are respectively:

$$
\begin{align*}
R^{(1)}_{\text{max}} &= 15X^{(1)} = (2,3,2,5,3)^T, \\
R^{(2)}_{\text{max}} &= 20X^{(2)} = (3,4,6,5,2)^T, \\
R^{(3)}_{\text{max}} &= 10X^{(3)} = (1,2,3,3,1)^T.
\end{align*}
$$

It can be obtained that the resource value range of each element in the matrix $R^{(1)}$, $R^{(2)}$, and $R^{(3)}$ is:

$$
\{0 \leq r^{(1)}_i \leq 2, 0 \leq r^{(2)}_i \leq 3, 0 \leq r^{(3)}_i \leq 3\} \leq 2, 0 \leq r^{(3)}_i \leq 5, 0 \leq r^{(3)}_i \leq 3\}
$$

(14)
By applying equations (12) and (13) to equation (11) and combining equations (14), (15), and (16), using MATLAB software, the optimization results of parallel iterative working time $T$ can be obtained under the condition of improved resource allocation uncertainties shown in Figure 3.

\[
\begin{align*}
0 < t^{(2)}_1 &\leq 3,0 < t^{(2)}_2 &\leq 4,0 < t^{(2)}_3 &\leq 6,0 < t^{(2)}_4 &\leq 5,0 < t^{(2)}_5 &\leq 2, \\
0 < t^{(3)}_1 &\leq 1,0 < t^{(3)}_2 &\leq 2,0 < t^{(3)}_3 &\leq 3,0 < t^{(3)}_4 &\leq 3,0 < t^{(3)}_5 &\leq 1, 
\end{align*}
\]

(15) (16)

It can be seen from Fig. 5 that each human resource working time $T$ is convergent. Figures 5 (a), 5 (b), and 5 (c) respectively show that the working time $T$ of the coupled task set converged to 10.4110 days under the resource allocation of mechanical engineers; the working time $T$ of the coupled task set converged under the resource allocation of mechatronic engineer 8.0987 days; under the allocation of structural engineer resources, the working time $T$ of the coupled task set converges to 16.0315 days. According to formula (5), the human resource with the longest execution time, that is, the structural engineer, determines the completion time of the entire development process, that is, the final completion time of the entire development process is 16.0315 days. Table 3 shows a comparative analysis of the data in Figure 5 and Table 2.
|                       | Optimization model of parallel iteration time under uncertain resource allocation | Improved parallel iteration time optimization model under uncertain resource allocation | Time reduction rate |
|-----------------------|---------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|---------------------|
| Mechanical engineer   | 16.4972 days                                                                     | 10.4110 days                                                                      | 36.89%              |
| completion time       |                                                                                 |                                                                                  |                     |
| Mechatronic engineer  | 12.3724 days                                                                     | 8.0987 days                                                                       | 34.54%              |
| completion time       |                                                                                 |                                                                                  |                     |
| Structural engineer   | 24.7449 days                                                                     | 16.0315 days                                                                      | 35.21%              |
| completion time       |                                                                                 |                                                                                  |                     |
| Final completion time | 24.7449 days                                                                     | 16.0315 days                                                                      | 35.21%              |

It can be seen from Table 3 that the task completion time under the uncertain resource allocation after the model improvement is shorter than the task completion time before the model improvement.

6. Conclusions
The uncertainty of resource allocation during the product development process will lead to an increase in the iteration time of the coupled task set, which is not conducive to the improvement of resource utilization. The analytic hierarchy process is applied to the resource allocation of the coupled task set, and the weight of each task to each type of resource is determined according to the demand-to-weight ratio of similar resources for each task. The uncertainty of resource allocation by experience can be optimized, so that Reduce the execution time of parallel iteratively coupled task sets under uncertain resource allocation conditions. This research provides a reference for optimizing resource allocation and reducing time in product design and development.

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