Scheduling Model and Algorithm of Construction Equipment under Milestone Constraint

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Abstract The scheduling of construction equipment is a means to realize network planning. With the large-scale and low-cost requirements of engineering construction, the cooperation among members of the engineering supply chain has become very important, and effective coordination of project plans at all levels to optimize the resource management and scheduling of a project is helpful to reduce project duration and cost. In this paper, under the milestone constraint conditions, the scheduling problems of multiple construction devices in the same sequence of operation were described and hypothesized mathematically, and the scheduling models of multiple equipment were established. The Palmer algorithm, CDS algorithm and Gupta algorithm were respectively used to solve the optimal scheduling of construction equipment to achieve the optimization of the construction period. The optimization scheduling of a single construction device and multiple construction devices was solved by using sequencing theory under milestone constraint, and these methods can obtain reasonable results, which has important guiding significance for the scheduling of construction equipment.
Key words Milestone; Equipment scheduling; Resource constraint; Algorithm analysis
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In the process of engineering construction, a large quantity of various construction equipment is needed, and the equipment scheduling scheme directly affects the progress and cost of a project. In the construction process, the reasonable scheduling of various construction equipment and the optimal utilization of construction equipment are one of the important factors affecting the construction progress and cost of a project. The scheduling of construction equipment is how to deal with the space-time relationship between construction activities and equipment under the conditions of satisfying the logical relationship between project activities, the duration bottom line of a project, the type and quantity of construction equipment and so on, so that construction equipment can maximize its organizational operation efficiency. Reasonable equipment scheduling can effectively improve the use efficiency of equipment, reduce the total cost of engineering construction projects, and solve the dilemma of construction equipment scheduling, which has a wide range of theoretical and practical significance for engineering project management. In this paper, the constraint conditions of milestones in a construction task was considered with certain resources, and the reasonable scheduling of multiple devices was studied to provide decision basis for contractors.

1 Theory of equipment scheduling with milestone constraint

1.1 Definition of scheduling Equipment scheduling problem is a kind of typical practical scheduling problem, and was paid attention to by enterprise engineers and management consultants as early as the beginning of last century, but at that time there were only some simple ideas, and there was no theory and practical application. For example, Gantt explained how to use visual charts to represent construction conditions. Coes described a mechanical scheduling technique that shares many features with modern "Kanban" systems. In order to ensure that a project is completed on schedule, resources such as labor force, construction machinery and equipment, and building materials should be organized according to the schedule plan of the network diagram, and reasonable equipment scheduling should be adopted to shorten the construction period. In construction, the process relationship is fixed, but the organizational relationship can be changed. Construction organization aims to shorten the construction period by changing the organizational relationship under the condition of limited resources, that is, the total construction period obtained by different construction equipment scheduling methods is different. However, when arranging the construction schedule, technicians did not consider the scheduling of construction equipment according to milestone constraint, and often arranged the scheduling sequence of construction equipment based on experience. As a result, the scheduling of construction equipment is not organized in the optimal order, and the construction period cannot be optimized[1].

1.2 Related parameters affecting equipment scheduling The main parameters to be analyzed in the mathematical model of project scheduling problem include task duration, relationship constraint, resource constraint and so on. However, the specific implementation and different combinations of these parameters will have a great impact on the actual project scheduling. The network characteristic parameters that need to be analyzed for project scheduling include the scale and shape of network, characteristic parameters of logical structure, the time characteristics of a pro-

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ject, and the demand and supply characteristics of project resources[2]. The main parameters are described as follows.

1.2.1 Network complexity. In different projects, the structure of parallel process and serial process is different. The more parallel process and the longer molding process of a project, the more complex the network. The of project network is a parameter that reflects the complexity of network structure. The larger the value of the complexity, the higher the complexity.

$$NC = \frac{|E|}{|V|} \tag{1}$$

1.2.2 Resource coefficient. The requirement of a task for resources will form the resource load of a project during the process of project scheduling. The larger the resource load, the more resources a project needs to configure. Resource coefficient RF reflects the demand of a task for various resources, and directly affects the resource load level of project scheduling.

$$RF = \frac{1}{J}\frac{1}{K}\sum_{j=1}^{J}\sum_{k=1}^{K}\mathrm{sgn}(r_{jk}) \tag{2}$$

$$\mathrm{sgn}(r_{jk}) = \begin{cases} 1, & r_{jk} > 0 \\ 0, & r_{jk} \leqslant 0 \end{cases} \tag{3}$$

If $RF = 1$, every resource is required for every task. $RF = 0$ means that no tasks require resources, and the problem of project scheduling degenerates into a resource-free problem of project scheduling. It can be seen that the larger the RF, the closer the demand relationship between a task and resources, and the more difficult it is to allocate resources in project scheduling.

1.2.3 Resource intensity. Resource intensity RS is used to describe the relationship between task resource demand and resource supply, namely the scarcity of resources.

$$RS_K = \frac{R_k}{\frac{1}{J}\sum_{j=1}^{J} r_{jk}} \tag{4}$$

The smaller the value, the scarcer the resourced. When resource intensity is low, a feasible schedule may not be obtained. Kolisch analyzed the operational effect of network complexity (NC), resource coefficient and resource intensity (RS) on computational complexity, and pointed out that network complexity (NC) has the least effect on computational complexity, while resource coefficient and intensity have significant effects.

1.2.4 Resource constraint intensity. Resource constraint intensity is also used to describe the degree of scarcity of a resource.

$$RS_K = \frac{\overline{r_k}}{R_k} \tag{5}$$

$$\overline{r_k} = \frac{\sum_{j=1}^{J} r_{jk}}{\sum_{j=1}^{J}\mathrm{sgn}(r_{jk})} \tag{6}$$

In the formula, $\overline{r_k}$ is the average demand for resource k.

2 Scheduling model and algorithm of a single device with a milestone

2.1 $1\,|r_j, prmp|L_{max}$ model and algorithm During the construction of the engineering task T_j, the task has different preparation time, and the task processing is allowed to be interrupted. The limited completion time of the task d_j is given as follows:

$$1\ |r_j,\ prmp|L_{\max} \tag{7}$$

In the above formula, the maximum delay time L_{max} is the objective function.

The optimal polynomial algorithm is adopted as follows:

(1) In the current tasks, the one with the least time limit is processed (if there are multiple tasks, either one of them is chosen).

(2) Whenever the processing of a task is completed or another task arrives, it turns to step (1) to re-determine the current processing task until all tasks are processed.

2.2 $1\,|r_j|L_{max}$ model and algorithm Task T_j has different preparation time, and task processing does not allow interruption of sequencing problems. The limited completion time d_j of task T_j is given as follows:

$$1\ |r_j|L_{\max} \tag{8}$$

The objective function is the maximum delay time L_{max}.

The branch and bound algorithm is used to solve the optimal scheduling of a single device. For the sequencing problem of n tasks, a complete search tree has n nodes.

(1) Layer 0 is the heel node, from which n nodes in layer 1 are generated, and each node corresponds to a partial ordering of tasks already scheduled in the first position.

(2) A node branch of layer 1 can produce $n-1$ nodes in layer 2, and each node corresponds to a partial ordering of tasks scheduled in the first two positions.

(3) A node branch of layer $r-1$ can produce $n-r+1$ nodes in layer r, and each node corresponds to a partial ordering of tasks scheduled in previous r positions.

(4) The lower boundary of each node is determined. A feasible order can be determined from a node in layer $n-1$, and the value of the starting objective function is as an upper bound of the value of the optimal sorting objective function.

(5) For nodes whose lower bound is not less than the upper bound of the current optimal objective function value, the nodes whose lower bound is less than the upper bound of the current optimal objective function value are branched to continuously improve the upper bound of the current optimal objective function value and then obtain the final optimization ranking (Fig. 1).

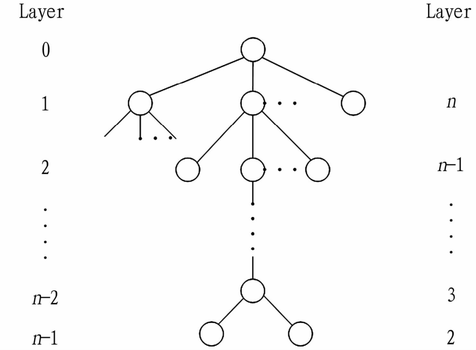

Fig. 1 Branch and bound diagram

In the branch process, not every node can branch. If a node is on layer $k-1$ and the corresponding tasks T_1, T_2, $\cdots$, T_{k-1} have been ranked in the previous $k-1$ positions, task T_k that meets formula (9) can be ranked in position k (producing nodes in layer k).

$$r_k < \min_{r_l \in \zeta}\{\max\{t, r_l\} + p_l\} \tag{9}$$

where ζ is the set of tasks that have not yet been sorted, and t is the completion time of task T_{k-1}.

2.3 $1|r_j, p_j=1|L_{max}$ model and algorithm If a task has different preparation times, task processing is not allowed to interrupt, and task processing time is unit time ($p_j=1$), the sequencing problem is as follows:

$$1|r_j, p_j=1|L_{max} \tag{10}$$

The objective function is the maximum delay time L_{max}.

The optimal scheduling scheme is solved using the following optimal polynomial algorithm:

(1) Among the current arrived tasks, the task with the least time limit is selected to process (if there are multiple tasks, one is chosen);

(2) When the processing of a task is completed, step (1) is conducted to re-determine the current processed task until all tasks are processed.

3 Scheduling model and algorithm of multiple devices with milestones

3.1 Problem description and hypothesis The scheduling problem of multiple devices can be described that m construction devices work in n construction stages, and the working sequence and time in each construction stage are different. Moreover, there are m construction processes in each construction stage. The working time of each construction device in each process is known, and the scheduling order of construction devices is determined by using the sequencing model to minimize the working time of the entire construction stage. The known conditions are as follows.

(1) The set of construction stages is $\delta=\{K_1, K_2, \cdots, K_n\}$, where K_i indicates the n^{th} construction stage ($i=1, 2, \cdots, n$).

(2) The set of multiple devices is $\zeta=\{P_1, P_2, \cdots, P_m\}$, where P_j stands for the j^{th} device ($j=1, 2, \cdots, m$).

(3) Process matrix is $A=(A_1, A_2, \cdots, A_n)$, and $A_i=(a_{1i}, a_{2i}, K, a_{ki}, \cdots, a_{mi})^T$, where a_{ki} means that the k^{th} construction device works in the i^{th} construction stage ($i=1, 2, \cdots, n$, $k=1, 2, \cdots, m$).

(4) The operation time of each construction device in various construction stages is $T=(T_1, T_2, \cdots, T_n)$, and $T_i=(t_{1i}, t_{2i}, \cdots, t_{ki}, \cdots, t_{mi})^T$, where t_{ki} is the operation time of the k^{th} construction device in the i^{th} construction stage ($i=1, 2, \cdots, n$, $k=1, 2, \cdots, m$).

(5) The start operation time of the k^{th} construction device in the ith construction stage is ES_{ik}, and the finish operation time of the k^{th} construction device in the i^{th} construction stage is EF_{ik}. The running distance of two adjacent construction devices j and $j+1$ is $d(P_j, P_{j+1})$.

To organize the construction, it is necessary to reasonably divide construction stages, and the labor input should meet construction needs. Various materials, components, construction machinery and equipment can ensure construction needs, and the following constraints should be met.

(1) The operation sequence of each construction stage must be fixed;

(2) Each construction device can only work in one construction stage at a time;

(3) The operation of construction devices in each construction stage is not allowed to be interrupted;

(4) Each construction stage shall undergo m construction processes, and continuous construction shall be carried out during the construction process.

To visualize the description of problems, job shop scheduling problem (JSP) is used to describe problems, and it is expressed as a graph $G=(N, A, E)$. N represents the set of nodes of the process; A, which is the set of conjunctive edges, refers to the sequence relationship of the process in the same construction stage, and is expressed by a one-way solid line; E wo-way dotted line. represents the set of disjunctive arcs, and refers to the sequence relationship of the same construction device in process. The organizational relationship is undetermined, so it is represented by a two-way dotted line. (P_j, K_i) indicates that construction device P_j works in construction stage K_i (Fig. 2). As shown in Fig. 2, start and end stand for the start and end of a project, $m=4$, $n=3$. (P_1, K_2) means construction device P_1 works in construction stage K_2. Process relationship in each construction stage is $p_1 \rightarrow p_2 \rightarrow p_3 \rightarrow p_4$. Because of the different ordering of construction stages, the scheduling sequence of construction devices is also different, so it is represented by a two-way dotted line.

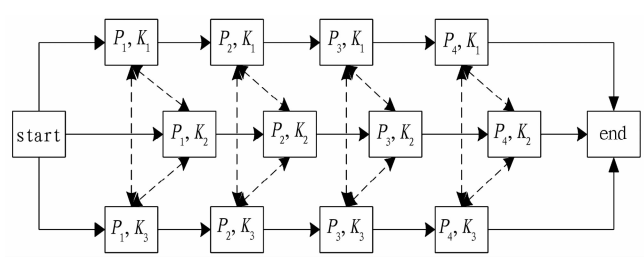

Fig. 2 JSP extraction diagram of a project

3.2 Scheduling model of multiple devices Taking the construction minimization and maximum completion time as the objective function, the following sequencing model of pipeline construction is established.

$$\min\{\max_{1\leqslant k\leqslant m}[\max_{1\leqslant i\leqslant n} t_{ki}]\} \tag{11}$$

The corresponding constraint conditions are as follows:

$$\begin{cases} E_{ij}+t_{ji}\leqslant E_{i(j+1)} \\ E_{ijk}+t_{ji}\leqslant E_{ghk} \\ t_{ji}\geqslant 0 \\ i=1, 2, \cdots, n \\ j=1, 2, \cdots, m \\ h=1, 2, \cdots, m \\ g=1, 2, \cdots, n \end{cases} \tag{12}$$

Formula (11) is the objective function, with construction minimization and maximum completion time. Formula (12) shows constraint conditions, showing the construction sequence of various processes in each construction stage; the meanings of these symbols are the same as before.

4 Algorithm analysis

4.1 Gupta algorithm Gupta algorithm is a heuristic algorithm proposed by Gupta to solve the job ranking problem. The complexity of the algorithm is $O\ (n\log n + nm)$. The calculation amount of the algorithm is relatively small, and it is a commonly used algorithm to solve the job ranking problem. Paterkovsky method is mainly used to determine the time interval of different water flows when the water beats are not equal. Firstly, the time of the water beats in each construction process is added together, and then the accumulated results of each adjacent construction process are dislocated by subtraction. Finally, the maximum is selected from the subtraction results, namely the water step distance of two adjacent construction processes in the same construction stage. By the combination of Gupta algorithm and Paterkovsky method, a hybrid algorithm is obtained to solve the optimization period of flow construction, which provides a practical calculation tool for organizing flow construction.

Step 1: The start time, duration and end time of each process in each construction stage of each work team is listed, and the operation time matrix of each construction stage is established.

Step 2: The Gupta heuristic algorithm is used to obtained the priority factor π_i of construction stage K_i, and construction stages are sorted according to priority factor.

Step 3: Paterkovsky method is used to calculate the flow distance of the sorted construction stages.

Step 4: The total construction period is calculated according to the flow distance and the total working time of the final sorted construction stages.

According to the set of construction stages $\delta = \{K_1, K_2, \cdots, K_n\}$, as well as the set of multiple construction devices $\zeta = \{P_1, P_2, \cdots, P_m\}$, a sequence matrix A is established by the Gupta heuristic algorithm as follows.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \mathrm{M} & \mathrm{M} & & \mathrm{M} \\ a_{m1} & a_{m2} & \mathrm{L} & a_{mn} \end{bmatrix} \tag{13}$$

When flow construction is conducted, the working time t_{ki} of the k^{th} construction device in the ith construction stage is determined, and the matrix T of working time in each construction stage is obtained.

$$T = \begin{bmatrix} t_{11} & t_{12} & \cdots & t_{1n} \\ t_{21} & t_{22} & \cdots & t_{2n} \\ \mathrm{M} & \mathrm{M} & & \mathrm{M} \\ t_{m1} & t_{m2} & \mathrm{L} & t_{mn} \end{bmatrix} \tag{14}$$

At first, the priority factor π_i of construction stage K_i is defined by this algorithm.

$$\pi_i = \frac{[e_i]}{\min_{k=1}^{m-1}(t_{ki} + t_{k+1,i})},\ i = 1, 2, \cdots, n \tag{15}$$

$$e_j = \begin{cases} 1, & p_{1j} < p_{mj} \\ -1, & p_{1j} \geqslant p_{mj} \end{cases}$$

All priority factors are sorted to determine the construction sequence of various construction stages. It is assumed that the set of reordered construction stages is $[K_1, K_2, \cdots, K_n]$, and the objective function is calculated according to the sorted construction stages.

$$\min\{\max_{1\leqslant k\leqslant m}[\max_{1\leqslant i\leqslant n} t_{ki}]\} \sum_{j=1}^{m-1} d(P_j, P_{j+1}) + \sum_{i=1}^{n} t_{mi} \tag{16}$$

4.2 Palmer algorithm In 1965, Palmer[3] proposed a heuristic algorithm to solve this scheduling problem of construction devices. At first, the priority factor π_j of the accident point J_j is defined by the algorithm as follows.

$$\pi_j = \sum_{k=1}^{m}\left(k - \frac{m+1}{2}\right)p_{kj},\ j = 1, 2, \cdots, n \tag{17}$$

A satisfactory scheduling scheme can be obtained by arranging all the accident points in the order that π_j does not increase.

4.3 CDS algorithm CDS algorithm is a heuristic algorithm given by Campbell *et al.* [4] in 1970 to solve the scheduling problem of construction equipment. The algorithm first generates m − 1 sorts, and then the best one is selected among them. The rescue times required for the accident point *Jj* on the two construction devices α_j and β_j are defined as follows.

$$\alpha_j = \sum_{k=1}^{i} p_{kj},\ \beta_j = \sum_{k=1}^{i} p_{m-k+1,j},\ i = 1, 2, \cdots, m-1;\ j = 1, 2, \cdots, n \tag{18}$$

When $i = 1, 2, \cdots, m-1$, $m-1$ groups of α_j and β_j can be obtained. Johnson algorithm can be used to obtain a sort, and a total of $m-1$ sorts can be obtained. The lowest value of the objective function is the optimal scheduling result.

5 Conclusions

Large construction projects have complex construction procedures, and there are many construction stages and limited construction devices. Milestones are taken as known conditions to study the sequencing problem of a single construction device, and three scenarios are respectively modeled and solved. The first scenario is the sequencing problem of maximum delay without preparation time, and the optimal scheduling of a single device is solved by using EDD rules. The second case is that the task has different preparation time, and the task chain is allowed to be interrupted. The optimal polynomial algorithm is used to solve the optimal scheduling of a single device. The third case is that the task has different preparation time, and the task chain is not allowed to be interrupted. The branch-and-bound algorithm is used to solve the optimal scheduling of a single device, which has a guiding effect on the scheduling of multiple construction devices. Milestones are taken as known conditions to study the sequencing problem of multiple construction devices. Considering the same sequence of operations, Palmer algorithm, CDS algorithm and Gupta algorithm are respectively used to solve the optimal scheduling of construction equipment to achieve the optimization of construction period. This model can well solve the scheduling research of equipment in the same sequence of construction. Only a part of the scheduling problem of construction devices under milestone constraints is studied in this paper. However, in practice, when there are two or more

(To page 41)

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(From page 35)

optimal scheduling schemes for construction equipment scheduling, decision makers may consider all scheduling sets that are optimal for the main objective, and then find the best scheduling for the secondary objective within these special scheduling sets. For example, it is worth further combining the main target time limit and the secondary target cost.

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