Research on resource-constrained project scheduling method based on heuristic priority rules

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Abstract

The traditional project scheduling problem only considers the logical constraints. However, there is a need to consider the resources such as labour, capital and other constraints. Resource constrained project scheduling problem (RCPSP) integrates logic and resource constraints, which are closer to the actual scheduling. And most of these problems belong to NP-hard problem, which have certain difficulty in solving process. And therefore, there is a very important significance to study in the RCPSP, especially in the theory and application. Among the many the RCPSP models, resource constrained project scheduling problem is the most fundamental, but also the most basic model. Most RCPSP research has focused on a single project scheduling problem. The main content of this article describes the single resource constrained project scheduling problem and establishes the according model. Then, it studies how to use heuristic priority rules for solving the single project scheduling problem. In addition, this paper finally simulates a single project scheduling as an example of mold production and solves it by using the heuristic algorithm based on priority rules in order to verify the effectiveness of the algorithm. It combines with the different schedule generation schemes and priority rules as well as compares the different solution results. The final outcome indicates that the combination of different priority rules and schedule generation schemes would influence the single project scheduling results.

Keywords: resource constraints, project scheduling, heuristic priority rules

1 Introduction

Project scheduling is one of the most important procedures in project management. How to deal with the various tasks in the project schedule is crucial for the project management. Generally speaking, the project scheduling is based on the scheduling objective, based on certain human, material and financial resources, based on the sequence of execution of each task. Through the reasonable arrangement, a reasonable schedule scheme is eventually emerging.

Usually, the project scheduling tools include Gantt chart and network plan technology. The earliest one is the Gantt Chart [1]. Gantt chart indicates the execution order of the tasks and the time parameters, so that the project members can intuitively understand each task starting time and the order of execution, which can effectively evaluate the whole project scheduling process. The network planning technology [2] is the emerging technology developed in the mid 50's twentieth Century, then is quickly popular into the project scheduling field. With the development of network technology, it produces two core technologies: the critical path method, CPM and plan evaluation and review technique, PERT [3]. The network planning techniques could demonstrate the entire process of project scheduling, which could be used to describe the constraints between each task. Its structure is illustrated in figure 1. Other methods, such as critical path method, plan evaluation and review technique have some serious limitations in the project task scheduling. It assumes that the constraint does not exist in the task allocation process. Accordingly, this article adopts a heuristic method to solve the resource constrained project scheduling problem. The article is organized as follows: the second section discusses the single project scheduling problem and the corresponding mathematical model; the third section elaborates the heuristic algorithm for solving project scheduling problem based on priority rules; the fourth section verifies the proposed algorithm by introducing an example of the single project scheduling in mold production; the last one is the summary and analysis and prospects for future research.

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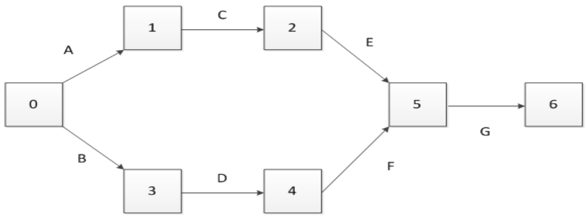


FIGURE 1 The network structure diagram.

2 An analysis and model establishment of project scheduling problem

Resource constrained single project scheduling problem (RCSPSP) [4] refers to the RCPSP problem which is for single project scheduling. The model is only applied to a project scheduling, logical and resource constraints between each task. It only considers renewable resources for each task specific constraints.

In a single project scheduling, the project includes J tasks. Structure for the project consists of a single code network chart (AON), where the nodes in the graph represent the task of the project, and directed arrows represent the constraint relationship between tasks. The first node and the last node are task 0 and task map in J respectively, which denotes the start time and end time for project. Moreover, execution time is 0 and there is no need to allocate resources. All tasks in the project have their corresponding duration d_j, start time ST_j and end time FT_j.

In the single project scheduling, there are constraints between each task. These constraints are usually referred to logical constraints and resource constraints. Logical constraints are described in specific performance for the precedence relation constraint among tasks. Each task must wait until its former task completed, i.e. the following up task is constraint by the former task. Secondly, as the unique to RCPSP resource constraints, they are usually referred that in the task execution process, each task needs to allocate different resources, and the number of resources is limited. The resource constraints are expressed as follows: in a K renewable resources in single project scheduling, the total resources of $k(k=1,2,\ldots,K)$ is R_k. The task j is required the renewable resources amount r_{jk} in the process of implementation. Then the constraint relationship is $\sum_{A_j \in I_t} r_{jk} \le R_k, \forall k, t$.

In resource constrained project scheduling problem, there is another important condition, besides the time parameters of the task constraint, which is objective function, the project optimization goal. At present, the objective function of time scope and resource scope are very popular in the single project scheduling. For the objective function of time scope, there are the minimum duration minFT_J, minimum project delay minmax$\{0,FT_j-d_j\}$, while for the objective function of resource scope, there is most common one minimum resource total cost $\min \sum_k C_k(R_k)$.

TABLE 1 The symbol lists of single project scheduling model

Symbol	Explanation
j	task index, j=1,2,…,J (J denote the total number of tasks)
t	time index, t=0,1,2,…,T (T denotes the upper limit of project makespan)
k	resource index, j=1,2,…,K (K denotes the total number of renewal resources required by a project)
d_j	the duration of task j
P_j	a immediate predecessor set of task j
S_j	a immediate successor set of task j
ST_j	the start time of task j
FT_j	the finished time of task j
R	the renewal resource set required by a project
R_k	the amount of resource k
r_{jk}	the amount of resource k take j requires
I_t	the execution task set at time t

According to the resource constrained project scheduling problem description, usually in a single project scheduling, the most common objective function is the minimum total duration. After meeting the logical constraints and resource constraints, there are reasonable arrangements for the task scheduling order, so that it produces the shortest total duration. The single project scheduling model in this paper proposes minimum total duration as its objective function. Accordingly, there are hypotheses below.

(1) For the precedence constraints, it only considers immediately executed task after the former task completed.

(2) The objective function is minimizing the project duration.

(3) Each project could not be interrupted, non suspension.

(4) The renewable resource constraints are concerned only.

The single project scheduling mathematical model of symbol is list in table 1. The mathematical model is established as follow.

$$\text{Min } FT_j \tag{1}$$

$$ST_j \ge FT_h, \forall h \in P_j, \forall j \tag{2}$$

$$\sum_{A_j \in I_t} r_{jk} \le R_k, \forall k, t \tag{3}$$

$$ST_j \ge 0, \forall j \tag{4}$$

where formula (1) is the minimum total duration objective function; formula (2) is the precedence relationship constraints, formula (3) is the resource constraint; formula (4) is the non negative constraint.

When solving the resource constraint of single project scheduling problem model, it is essential to find a suitable schedule for each task to determine a reasonable start time to meet the constraint conditions. The project schedule can be represented as an array, namely $S=(s_1, s_2,\ldots, s_J)$. Figure 2 shows a single project scheduling example of J=9. The project has a renewable resource only, i.e. K=1, the total amount of resources R=4. Each task's duration and resource requirements are remarked in the AON diagram. Task 1 and task 9 are the start task and the finish task respectively, which do not take up any resources.

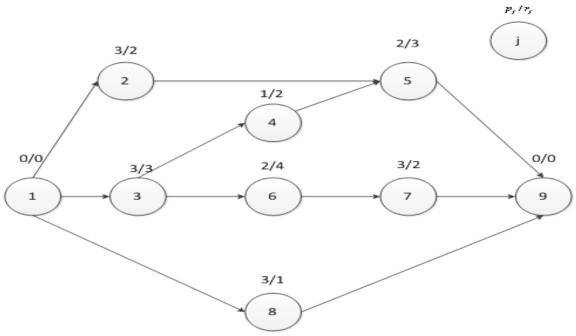


FIGURE 2 The single project scheduling paradigm.

3 Solution to the project scheduling problem based on priority rules

A heuristic algorithm is proposed by Kelly. Project scheduling is concerned with single-item or small batch production where scarce resources have to be allocated to dependent activities over time. More specifically, the exact and heuristic algorithms for the single-mode and the multi-mode case are reviewed, for the time–cost trade-off problem, for problems with minimum and maximum time lags, for problems with other objectives than make span minimization [5]. The well-known resource-constrained project scheduling problem (RCPSP) summarizes and categorizes a large number of heuristics that have recently been proposed in the literature. Most of these heuristics are then evaluated in a computational study and compared on the basis of our standardized experimental design. Therefore, the researchers have put forward the different solutions based on heuristic algorithm [6].

A new heuristic called self-adapting genetic algorithm employs the well-known activity list representation and considers two different decoding procedures. An additional gene in the representation determines which of the two decoding procedures is actually used to compute a schedule for an individual. This allows the genetic algorithm to adapt itself to the problem instance actually solved. Computational experiments show that the proposed heuristic is among the best ones currently available for the RCPSP [7]. Because this algorithm is relatively simple, it is quite popular. With the RCPSP expansion and model complexity, the efficiency of a heuristic algorithm for single channel is greatly reduced.

The project scheduling problem involves the scheduling of project activities subject to precedence and/or resource constraints. Despite all these efforts, numerous reports reveal that many projects escalate in time and budget and that many project scheduling procedures have not yet found their way to practical use. Herroelen [8] provides a generic hierarchical project planning and control framework that serves to position the various project planning procedures and discuss important research opportunities, the exploration of which may help to close the theory-practice gap [8]. The heuristic algorithm with various combinations of schedule generation mechanism and priority rule is called multi channel algorithm. The following ones are the common multi channel heuristic algorithms.

(1) Multi priority rule method. The method selects a schedule generation mechanism, and pursues the scheduling through the different priority rules.

(2) Forward and reverse backtracking method. This algorithm selects a schedule generation mechanism. After the repeated forward calculation and reverse calculation, it produces a series of project scheduling.

(3) Sampling algorithm. Sampling algorithm usually use only one schedule generation scheme and only one priority rule. However, in real situation, it determines the task scheduling via the probability of task priority value calculation, not according to the task priority value.

(4) Adaptive heuristic algorithm. The algorithm has high elasticity. It firstly selects the combination of schedule generation mechanism and priority rules according to the specific task quantity, constraint condition, and therefore it is greatly flexible.

Priority rule mechanism used in this paper is the generation mechanism of parallel and serial schedule based on the serial SGS with task as the phase variables, composed of J phases. Each phase of the $g(g=1,2,\ldots,J)$ corresponds to an incomplete plan task set PS_g and a feasible task set D_g, where the incomplete task set PS_g contains all the tasks which have arranged the start time, while the feasible task set D_g contains all the tasks which have not arranged the start time, but have already arranged all the preceding task, i.e. the task precedence task have been included in the incomplete task plan. At each new stage g, serial SGS would choose maximum priority coefficient task j^* from D_g into the current PS_g according to the priority rules in order to meet the precedence relations and resource constraints, as well as assign the specified start time, ST_{j^*} for task j^* and allocate resources. It repeats the scheduling, gradually extending PS_g, until the completion of the whole project schedule. Set all the tasks carried out in the time t as I_t, where $R_k(t)=R_k-\sum_{j\in I_t} r_{jk}$ is the remaining amount of the k resource at time t, and $v(j)$ is the priority coefficient for task j in D_g. Consequently, the serial scheduling generation mechanism of the process is illustrated in Figure 3.

Initialization: g=1, FT_1=0,PS1={1};
While $g<J$ do phase n
Begin
Calculate D_g, $R_k(t), k=1,2,\dots,K, t=FT_g$;
$j^*=\min_{j\in D_g}\{j|v(j)=\max_{i\in D_g}\{v(i)\}\}$; //select the maximum priority coefficient task j* from Dg //
$ES_{j*}=\max\{FT_h|h\in P_j\}$; //Calculate the earliest start time of task j*//
$FT_{j^*}=\min\{t|t\geq ES_{j^*}, r_{kj}\leq R_k(\tau), k=1,2,\dots,K, \tau=t,t+1,\dots,t+P_{j^*}\}+d_{j^*}$;//Calculate the finish time of task j*//
$PS_{g+1}=PS_g\cup\{j^*\}$;
g=g+1;
END;

FIGURE 3 The serial scheduling generation mechanism.

Parallel scheduling generation mechanism adopts the time as phase variable, contains a maximum of J phases. Each phase $g(g=1,2,\dots,J)$ corresponds to a scheduling time t_g. Set C_g as the completed task set at time t_g, and A_g as the proceeding task set at time t_g and D_g as the feasible task set at time t_g, where D_g contains all the tasks meeting the precedence relations and resource constraints which can be started at time t_g. At each stage, there are the following two steps for parallel schedule generation mechanism. (1) Determine the present time t_g. Exclude all the tasks of finish time equating to time t_g from A_g, then add them to the completed task set C_g, and update the feasible task set D_g. (2) In accordance with the principle of priority tasks, select the greater priority coefficient task j* from D_g, start the task from the current phase t_g, then shift the task j* from the feasible task set D_g to the proceeding task set A_g. Repeat step (2) until the feasible task set D_g is null, then move on to the next phase. Finally, when all the tasks have been belonged to the completed task set C_g or the proceeding task set A_g, the scheduling mechanism finishes. Set $R_k(t_g)=R_k-\sum_{j\in A_t}r_{jk}$ as the remaining amount of k resource at time t, where $v(j)$ is the priority coefficient D_g of task j. The parallel scheduling generation mechanism of the process is illustrated in Figure 4.

Initialization: g=1, t_g=0, D_g={1}, A_g=C_g=∅, $R_k(t_g)=R_k, k=1,2,\dots,K$;
While $|A_g\cup C_g|<J$ phase g
Begin
(1) $t_g=\min\{ST_j+d_j|j\in A_{n-1}\}$;
$A_n=A_{n-1}\setminus\{j|j\in A_{n-1}, ST_j+d_j=t_g\}$;
$C_n=C_{n-1}\cup\{j|j\in A_{n-1}, ST_j+d_j=t_g\}$;
Calculate $R_k(t_g)$ (k=1,2,…,K) & D_g;
(2) $j^*=\min_{j\in D_g}\{j|v(j)=\max_{i\in D_g}\{v(i)\}\}$;
$ST_{j^*}=t_g$;
$A_g=A_g\cup\{j*\}$;
Calculate $R_k(t_g)$ (k=1,2,…,K) & D_g;
If $D_g\neq\varnothing$ Then GOTO Step(2) ELSE n=n+1;
END

FIGURE 4 The parallel scheduling generation mechanism.

In addition, due to the serial and parallel scheduling process described above, there is a process in the selection of maximum priority coefficient task j^* from the feasible task set D_g. The value of the priority coefficient here is determined by the priority rules, and therefore there is a need for analysis on various priority rules. Specifically, priority rules refer to the expected generation mechanism that according to certain rules, each task priority coefficient is assigned in a feasible task set, which determines the task start time and the order of execution. There are four priority rules network-based rule, NBR, critical path-based rule, CPBR, resource-based rule, RBR, composite rule, CR. By using the iterative forward-backward scheduling technique, its application in real projects and comparison with other scheduling schemes confirmed that the proposed algorithm is capable to generate effective schedules for multiple projects with limited renewable resources [9].

4 Case study

In order to verify the validity of the algorithm, the concrete examples of the resource constrained project scheduling problem in this section are listed. The heuristic algorithm based on priority rules provides solution and the comparison of serial schedule generation scheme and parallel schedule generation scheme, and the effects of different priority rules for different feasible solutions.

This scheduling model assumes that a single project scheduling has 7 tasks, the scheduling process only uses 1 renewable resource, and the renewable resources amount is 5. According to the precedence task constraint relation, the established network diagram is illustrated in figure 5. The task execution time d and resource usage r are listed in Table 2. Without taking into account the various task resource constraints, the earliest start time and latest start time are listed in Table 3. Under the condition of no resource constraints, the earliest finish time of completed project is for 28 days.

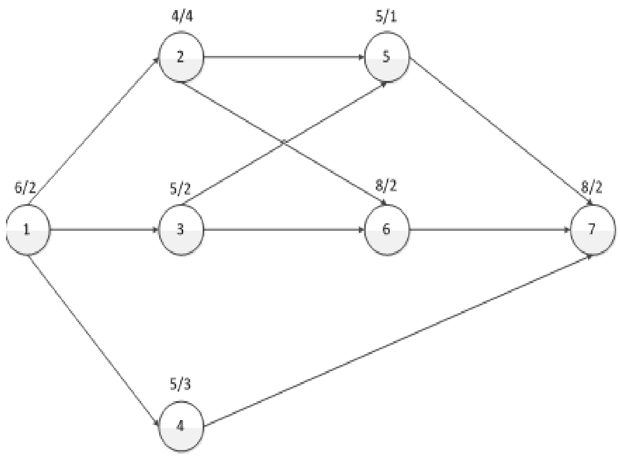


FIGURE 5 The case of single project scheduling.

TABLE 2 Each task execution time and resource usage

Task *j*	Earliest start time *ES*	Latest start time *FS*
1	6	2
2	4	2
3	5	2
4	5	3
5	5	5
6	8	2
7	8	2

A feasible schedule serial schedule generation scheme with arbitrary priority rules can be obtained in this project. Here, firstly determine the shortest duration for the task priority rules. Then the algorithm process is described as follows.

The first phase: initialize the feasible task set D_1, D_1={1}. The task 1 is scheduling preferentially, start time is 0, the execution time is 6 days, the allocation of resources is 2.

TABLE 3 Each task earliest start time and latest start time.

Task *j*	Execution time *d*	Resource usage *r*
1	0	0
2	6	7
3	6	6
4	6	14
5	11	11
6	11	14
7	19	19

The second phase: Task 2, 3, 4 consist of D_2, namely D_2={2,3,4}. According to the priority rule of the shortest duration, it schedules task 2. Set task 2 start time is 6, the execution time is 4 days, the allocation of resources is 2.

The third phase: D3={3,4}, the duration of task 3 and task 4 are both equal to 5. There is a need to use supplementary rules, namely the minimum number of priority scheduling rules. Therefore, the task 3 is scheduling preferentially. Set the start time is 10, the execution time is 5 days, the allocation of resources is 2.

The fourth phase: D_4={4,5,6}. According to the supplemental priority rule and minimum time priority rule, the task 4 is scheduling preferentially. Because the required resources of task 4 and task 3 both are 5, it can schedule the resource allocation simultaneously. Set start time is 10, the execution time is 5 days, the allocation of resources is 3.

The fifth phase: D_5={5,6}. According to the priority rules, the task 5 is scheduling preferentially. Set the start time is 15, the execution time is 5 days, the allocation of resources is 5.

The sixth phase: D_6={6}. Because the task 5 has exhausted 5 resources, the task 6 cannot share the resources with task 6. Set the start time is 20, the allocation of resources is 1.

The seventh phase: D_7={7}. After task 6 completing, task 7 is scheduling. Set the start time is 28, the allocation of resources is 1.

Through the above seven phases of scheduling, a feasible schedule set D_j is null. The scheduling finishes. A feasible planning project produces (represented by the task list form): {1,2,3,4,5,6,7}. The progress of the whole project arrangement is illustrated in figure 6.

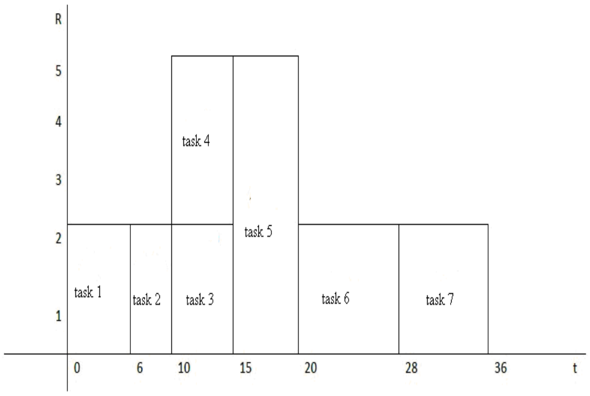


FIGURE 6 The whole project scheduling arrangement.

Secondly, it adopts the combination of the serial schedule generation scheme and the minimum time priority rule for the solution. The total time delay refers to the each task differences of the earliest start time and latest start or earliest finish time and latest finish time in project scheduling. According to the time parameter table of the project schedule in the former section, the critical path under the condition of non resource constraints is 1-3-5-7. The algorithm process is described below.

The first phase: D_1={1}. The task 1 is scheduling preferentially. The start time is 0, the execution time is 6, the allocation of resources is 2.

The second phase: D_2={2,3,4}. Based on priority rules, the task 3 is scheduling preferentially. The start time is 6, the execution time is 5, the allocation of resources is 2.

The third phase: D_3={2,4}. Based on priority rules, the task 2 is scheduling preferentially. The start time is 11, the execution time is 4, the allocation of resources is 2.

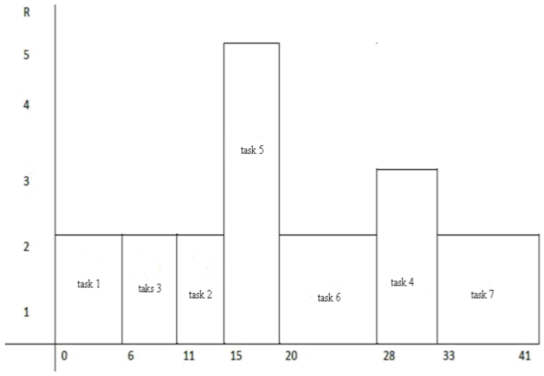
The fourth phase: D_4={4,5,6}. Based on priority rules, the task 5 is scheduling preferentially. The start time is 15, the execution time is 5, the allocation of resources is 5.

The fifth phase: D_5={4,6}. Based on priority rules, the task 6 is scheduling preferentially. The start time is 20, the execution time is 8, the allocation of resources is 2.

The sixth phase: D_6={4,7}. Based on priority rules, the task 4 is scheduling preferentially. The start time is 28, the execution time is 5, the allocation of resources is 3.

The seventh phase: D_7={7}. Based on priority rules, the task 7 is scheduling preferentially. The start time is 33, the execution time is 8, the allocation of resources is 2.

Through the calculation above, we can draw the conclusion that the feasible scheduling using the minimum total time difference priority rule is {1,3,2,5,6,4,7}.The exhaustive arrangement is illustrated in figure 7.



FIGURFE 7 The whole project scheduling arrangement.

The results show that under the same schedule generation mechanism, the different feasible schedules are calculated through priority rule. And thus, it will have a direct impact on the quality of project scheduling.

(2) The parallel schedule generation scheme for the solution

Here, another generation mechanism is used to solve the above examples, namely the use of parallel schedule generation scheme, and the selection of the most follow-up task as the priority rule. Let C_g the completed task set, A_g proceeding set at the time t_g, D_g the feasible task set at time t_g. The process is described as follows.

The first phase: D_1={1}. Allocate task 1. The current time is t_1=0, task 1 the start time is s_1= t_1=0, the resource allocation is 2, execute task set A_1={1}.

The second phase: the current time is t_2=6, D_2={2,3,4}. The subsequent task number of task 3 and task 2 is same. According to supplemental priority rule, task 2 is scheduling preferentially. The start time of task 2 is s_2=t_2=6, resource allocation is 2. After refreshing the remaining supply renewable resources, task 4 cannot continue to supply. So calculate D_2={3}. The task 3 is scheduling preferentially. Set the start time is s_3=t_2=6, the resource allocation is 2. Repeat calculation D_2=∅, enter the third phase.

The third phase: the calculation of the current time is t_3=11, D_3={4,5,6}, A_3=∅, C_3={1,2,3}. Task 4 is scheduling preferentially. Set the start time is s_4=t_3=11. Then A_3={4}, refresh remaining amount of renewable resources, task 5 cannot supply resources. And therefore, D_3={6}, task 6 is scheduling. Set the start time is s_6=t_3=11, then A_3={4,6}. Repeat calculation, D_3=∅, enter the next phase.

The fourth phase: the calculation of the current time is t_4=19, D_4={5}. The task 5 is scheduling preferentially. Set the start time is s_5=t_4=19, A_4={5}, the resource allocation is 5. Repeat calculation, $D_4=\varnothing$, enter the next phase.

The fifth phase: the calculation of the current time is t_5=24, D_5={7}. The task 7 is scheduling preferentially. Set the start time is s_7=t_5=24, the resource allocation is 2. Then, finish the scheduling.

Through the calculation, we can draw a conclusion that the feasible scheduling using parallel schedule generation scheme and most subsequent tasks is {1,2,3,4,6,5,7}. The specific scheduling arrangement is illustrated in figure 8.

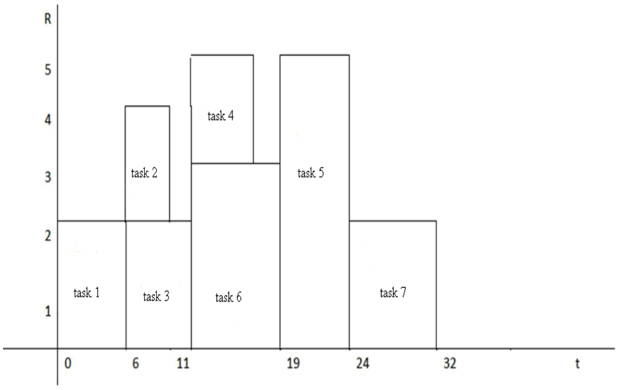


FIGURE 8 The whole project scheduling arrangement.

The examples model above verifies the feasible scheduling priority rule based heuristic algorithm which can obtain the resource constrained project scheduling. And the task scheduling would be different by using task serial and parallel generation mechanism respectively. Its practical application should be based on specific issues to choose the schedule generation scheme. Finally, the experiment also proves that the different priority rules will have an impact on the results under the same schedule generation mechanism.

5 Conclusions

Firstly, the traditional project scheduling problem background and related problem solving tools are introduced. Then, the single project scheduling problem and resource constraints are described. After that, a mathematical model is established. Based on the heuristic algorithm research on priority rules, two aspects from the schedule generation mechanism and priority rules are studied. The serial schedule generation scheme and parallel schedule generation scheme algorithm are introduced. There is an analysis of the characteristics of various priority rules. Finally, an example of mold production for single project scheduling is demonstrated. The example of the priority rule heuristic algorithm is presented. During the solution process, there are comparison and analysis of the different effects on the results of serial schedule generation scheme and parallel schedule generation mechanism. And there is another analysis on results via the combination of different schedule generation mechanism and different priority rule. After all, the heuristic algorithm based on priority rules indicates the validity single project scheduling problem under the resource constraints.

The flaw of the article is the selection of the heuristic algorithm based on priority rules for the solution to the single project scheduling problem. Although the use of the algorithm obtains the scheduling solution, for some complex project scheduling problem, the algorithm could not obtain the optimal solution, only a series of feasible solutions. In order to get the optimal solution, these feasible solutions are required to continue some subsequent operations. Therefore, the further studies are needed upon the intelligent algorithm from the aspect of algorithm, which could be applied to some complex project scheduling problem.

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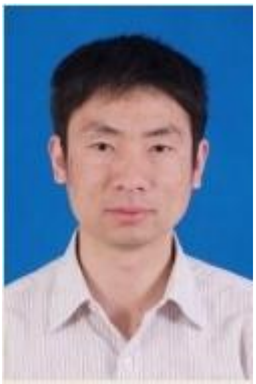

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