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Complex Equipment Remanufacturing Schedule Management Based on Multi-Layer Graphic Evaluation and Review Technique Network and Critical Chain Method

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ABSTRACT In order to solve project schedule delays caused by resource conflicts and uncertainty of the environment, work duration, and logical relationship, this paper proposed CCPSP (critical chain project scheduling problem) optimal scheduling model which integrates CCM (critical chain method) and multi-level GERT (graphical evaluation and review technique) network. DEACA (differential evolution ant colony algorithm) is designed to solve the problem, in which DE (differential evolution algorithm) is used to deal with the cross problem and mutation problem, and ACA (ant colony algorithm) is used to deal with each stage of the optimization process. The neighborhood structure is introduced to reduce the invalid search. By storing the non-dominated Pareto optimal solution in external files, the Pareto optimal frontier is obtained. This paper makes full use of the advantages of the two algorithms to achieve fast convergence and a global search for optimal solutions. At the same time of seeking the optimization algorithm, considering the multi-resource constraints, environmental uncertainties and other factors of the project, a buffer is set up, and a ''minimum duration - maximum robustness'' project schedule is formulated. Finally, through the analysis and verification of the project example, it shows that the project schedule made by this method is feasible.

INDEX TERMS Graphic evaluation and review technique simulation (GERTs), critical chain method (CCM), critical chain project scheduling problem (CCPSP), schedule plan, differential evolution ant colony algorithm (DEACA), schedule buffer.

I. INTRODUCTION

Complex equipment refers to large and medium-sized scientific and technological products, such as military and civil aircraft, complex equipment, ships, railway locomotives, large construction machinery, and heavy machine tools, which play an important supporting role in national economic, social development and national defense security. Complex equipment has the typical characteristics of a complex structure, long production cycle, and high development cost. Its manufacturing level is the concentrated embodiment of a country's scientific and technological strength, comprehensive national strength, and international competitiveness [1]–[3]. Facing the external environment of sluggish global economic development and increasing the financial pressure in various countries, developed countries in Europe and the United States have taken the lead in carrying out the remanufacturing of complex equipment. While maintaining their global leading position in the economy and military, they have also significantly reduced the production cycle and overall investment of complex equipment. The so-called complex equipment remanufacturing refers to a series of technical measures or engineering activities that aim at the leapfrog improvement of the performance of waste equipment and take advanced technology and industrial production as means to repair and transform the waste complex equipment. It is an advanced stage of equipment maintenance, with the following advantages: the quality and performance of remanufactured equipment reaches or exceed the new products, while the cost and production cycles are only 50% of the new equip-

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ment, while energy-saving is 60% and material saving is 70% [3]. The implementation of the remanufacturing of complex equipment has significant economic, military and social benefits, and has become a strategic choice of countries around the world to promote economic development and maintain national security.

Currently in China, the remanufacturing of complex equipment adopts the organization mode of ''main manufacturer - supplier''. Its production has the following typical characteristics: first, the networked collaboration between production. There are a large number of remanufacturing collaborative works between the main remanufacturer and multiple first-class remanufacturing system suppliers in different places, showing networked collaborative production; second, the critical data required for production has strong randomness and uncertainty. The wear and damage degree of complex equipment is different due to the difference in using conditions (including using the environment and working condition, using frequency and using time), which leads to the strong randomness and uncertainty of critical data onto remanufacturing production. For example, due to the different degree of wear and tear of waste parts, there are three kinds of remanufacturing work in the future, which are ''directly entering the component library'', ''implementing the component remanufacturing'' or ''waste treatment'', and each of them has a certain probability. Additionally, the remanufacturing of parts will take place once or even many times of repair, which will lead to the formation of the working circuit. At the same time, the remanufacturing duration, remanufacturing yield, and other critical production data are uncertain. Therefore, Complex Equipment Remanufacturing forms a cross-regional and multi-level collaborative network of complex equipment remanufacturing production. Schedule management is one of the three objectives of complex equipment project management, and it is an important guarantee to meet the high requirements of complex equipment projects for the precise delivery time [4]. At present, there are still a series of difficult problems with the collaborative management of production schedule, such as ''the lack of collaborative network framework'' and ''the critical chain of collaborative network and the control of the best production buffer are not accurate'', which are most concerned and puzzled by the complex equipment remanufacturing enterprises.

The optimization of traditional project schedule control management methods and the exploration of new methods of schedule management had always been one of the issues that scholars at home and abroad pay close attention to. A large number of scholars at home and abroad have conducted a lot of elaboration and research from different levels and angles [5]–[9]. The project schedule is an activity to determine the process content and sequence relationship of the project implementation process, allocate various resources used in the implementation process and make specific time arrangement so that the project can be completed within the specified time, to control costs and save time. Since the 1950s, with the improvement of the complexity of the project, the traditional schedule management methods such as milestone method and Gantt chart could not well reflect the logical relationship between the processes in the construction, the importance and the impact on the subsequent processes, so the network planning technology represented by CPM (critical path method) and PERT (Program Evaluation and Review Technique) came into being. Ren Zhen studies the application of an improved earned value method based on CPM in the implementation and management of a large scientific research project [10], Wu Feifei *et al.* put forward a project duration risk assessment method based on PERT under the influence of many factors [11], but actually, both CPM and PERT are limited in its application, there are three reasons: Above all, they are all limited to the range of positive network structure. Every activity in the network must be realized, and there is no possibility of probability branching. After every event is realized, there is no room to choose activity or decision-making; Secondly, there is no strongly connected component in CPM / PERT network, that is, loops (or strongly connected) in the network are considered incompatible factors and must be excluded, which excludes feedback link which is a very rich modeling field; Thirdly, the activity cycle is limited to β distribution, which has subjective components in theory and practice. The activity cycle can be different distribution according to nature and probability characteristics of various work. Besides, the calculation method cannot completely and accurately reflect the statistical characteristics of β distribution. In most cases, it will lead to large errors due to deviation from the initial assumption. In reality, the working duration and logical relationship are often uncertain, and some processes of memory and some lessons can be learned should be reflected on the form of the feedback loop in the network. The emergence of the GERT random network solves the above problems well.

The main characteristic of the GERT random network is that nodes and activities are random, the input and output logic of nodes are diverse, and it is a dynamic description of a system. With the execution process of the network, the implementation of nodes reflects the emergence of discrete- random events, and the execution process of activities is the advancement of system time (represented by simulation clock time). Therefore, GERT (graphical evaluation and review technique) random network simulation is still a form of discrete system simulation.

In the GERT random network, there are only ''XOR'' type input nodes and probability type output nodes, which allow the emergence of loops. The probability distribution is used to describe the duration, and the network state transition is used to describe the objective process. It can be said that the GERT network is a Markov process of the form of a network, but it belongs to a semi Markov process because of the need for a certain random time for state transition. The solution to the GERT network has an analytical method and simulation method. The memory in the actual process makes the analytic method of GERT Network limited to the application. Considering that, people found a kind of stochastic network that can deal with both Markov type and non-Markov type at the same time, that is, GERTs stochastic network simulation technology.

After CCM (Critical Chain Method) was putting forward, a new method of project management was created, which broke the leading position of network planning technology. CCM thinks that the logical relationship between processes and the problem of limited resources is equally important. CCM is a combination of traditional network planning technology, project scheduling problem, and management art. The critical chain in CCM is a task sequence that restricts the whole project duration. The main difference between CCM and traditional methods like PERT and CPM is that CCM considers resource constraints and resolves resource conflicts.

Based on the methods and algorithms derived from constraint theory, critical chain project management was first proposed by Goldratt. Goldratt believed that the 50% probability completion time is used as the estimated time of the process instead of the completion probability 90% of the time is estimated, and then the safety time reserved for each operation is separated. At the same time, the logical relationship and resource constraints on each operation are considered. On this basis, the critical chain of the project is identified, and the project buffer, import buffer and resource buffer are set as the tools of progress control. By applying the aggregation principle to schedule management, the safety time of operation forms project buffer (PB) and feeding buffer (FB) through the aggregation principle, while resource buffer (RB) does not take up time. The aggregation principle is initially applied to risk and inventory management, and the introduction to aggregation principle to project schedule management can effectively explain the problem of shortening the construction period under the same completion probability.

The critical chain method can effectively solve the scheduling optimization problem with limited resources when the work duration and logical relationship are determined. However, due to the influence of many factors in the actual work, the work duration and logical relationship between the work are uncertain. The traditional method based on CCM is difficult to solve this problem. The GERTs (Graphic Evaluation and Review Technique simulation) is only limited to solve the total duration and completion probability problems when the work duration and logical relationship are uncertain, but it cannot solve the optimization of resource-limited problems. Therefore, it is of great significance of theoretical research and practical application to explore how to solve the optimization of resource-limited schedule under the condition of uncertain working duration and logical relationship. In other words, it is very meaningful to realize the organic integration of GERT and CCM.

At present, China's complex equipment remanufacturing industry is still in its infancy, and the model and method of production schedule collaborative management under the multi-level networks environment still need to be further studied, the specific performances are summarized as follows: Above all, the failure to build a GERT network management-control model and framework for complex equipment remanufacturing production schedule coordination has led to production schedule delay or even out of control and other adverse situations. Additionally, the integration research of GERT network theory and critical chain technology has not been realized, the critical chain of collaborative GERT network cannot be accurately identified and optimal production buffer cannot be effective design, above questions make it difficult to generate the most concerned production schedule collaborative optimization scheme for complex equipment remanufacturing enterprises.

Because of this, this paper will realize the organic integration of multi-layer GERT network and critical chain, establish a multi-objective resource-constrained project scheduling model of ''duration minimization and robustness maximization'' and design algorithm to solve it, effectively identify its critical chain and scientifically design the optimal production buffer, to improve the efficiency and ability to remanufacture management and control of complex equipment. The research can provide decision support for complex equipment remanufacturing enterprises to accurately control the critical nodes of the project, to provide a necessary guarantee for the production schedule to be completed as scheduled.

II. PROBLEM DESCRIPTION

RCPSP (Resource-Constrained Project Scheduling Problem) generally aims to find the scheduling scheme for the shortest duration (or the least cost). The project is composed of a series of interrelated activities. Its scheduling decision needs to meet the temporal constraints and resource constraints on project activities at the same time, to optimize the management objectives [12]. MRCPSP (Multi-mode Resource-Constrained Project Scheduling Problem) is an extension of traditional RCPSP, it considers that each activity in a project has a variety of execution modes that can be selected, each execution mode corresponds to a certain duration and resource requirements. During scheduling, it can dynamically select the execution mode and its attributes. MRCPSP mainly studies how to arrange the execution mode and start time of each activity based on the project activity network diagram to meet the constraints on resources and activity sequence, to make the project schedule shortest. Its essence is to find the best combination of each activity execution mode and start time [13]. Compared with the single-mode scheduling problem, MRCPSP, which is under resource constraints, not only need to select the execution mode of each activity in the project, but also need to determine the start-up period of the activity. It is an NP-hard problem with complex nonlinear characteristics, which is difficult to be solved by precise algorithms.

CCPSP (critical chain project scheduling problem), as the issue to be studied in this paper, has many similarities with MRCPSP. Both of them take the project duration as the objective function and are constrained by the pre - tight relationship and resource supply. However, based on MRCPSP, CCPSP considers all kinds of uncertainties that may occur in the process of project implementation and adds the concepts of project buffer and input buffer. The specific performances are as follows: (1) When people use the model of MRCPSP to build the project plan, the planned duration of tasks is determined, and the planned duration of each task contains sufficient safety time. CCPSP uses the most likely completion time (i.e. 50% of the possible completion time) as the task duration to avoid the risk of delay caused by student's syndromes; (2) The project buffer is embedded after the task is finished, and the input buffer is embedded between the non-critical chain and the critical chain to absorb the risk of project delays.

MRCPSP itself is a well-known NP-hard, so it is more difficult to solve CCPSP. Although the current research has discussed the identification of critical chain and the design of project buffer, there is no clear answer about how to determine the only critical chain in the project and resolve the secondary resource conflicts when embedding buffer. For a complex project, different scheduling schemes will produce different project plans, and each plan corresponds to its critical chain. How to find an optimal or suboptimal CCPSP plan also needs a reasonable model and algorithm.

III. DEFINITION AND PARAMETERS OF CRITICAL CHAIN IN GERTS STOCHASTIC NETWORK PLANNING

A. DEFINITION OF THE CRITICAL CHAIN IN GERTs STOCHASTIC NETWORK PLANNING

For a given GERTs network diagram, the network is simulated under consideration of resource constraints and network logic. In each simulation, the parameters in each process are randomly sampled and assigned, and a corresponding positive network is obtained. The longest completion path, completion period and implementation probability are counted. After n times of simulation, the path of the network will appear some statistical regular pattern, among which the path with the most times is called the critical chain of GERTs network, which is the critical chain in the statistical sense. After n times of simulation, the path of the network will appear some statistical rules, among which the path with the most times is called the critical chain of GERTs network, which is the critical chain in the statistical sense.

In each simulation process, the parameters of each process are obtained by random sampling, so the longest completion path obtained each time cannot represent the critical chain of the network, and the critical chain with statistical significance can be obtained only after many simulations. The definition of critical chains based on GERTs can be described in the following example.

For example, the logical relationship and parameters of each operation of a project are shown in Figure 1. Assuming that the operation duration follows a constant distribution, the numbers in brackets above the arrow represent the probability, time and required resource quantity of the operation respectively. For example, the (1,2,1) above the 1-2 operation

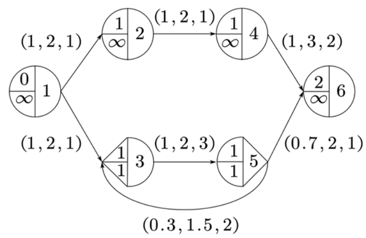


FIGURE 1. The GERT network plan diagram.

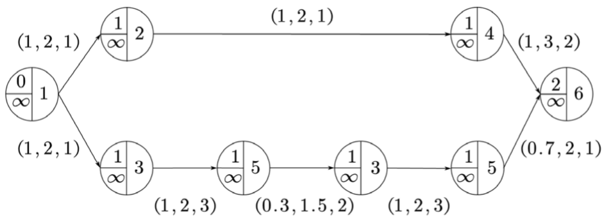


FIGURE 2. The GERT diagram for feedback loop implementation.

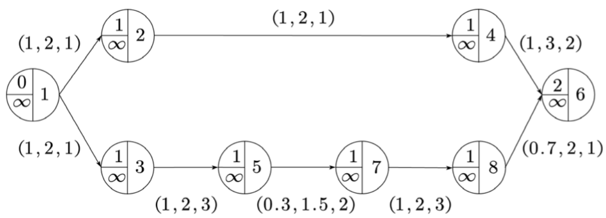
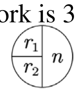


FIGURE 3. The GERT diagram after eliminating duplicate codes.

represents the probability of implementation, the required time is a constant of 2 days, and the required resource quantity is 1 unit. Now assume that the resource limit of the project network is 3.

In,  r_1 refers to the number of first releases of the node, That is when the node is implemented for the first time, the number of its predecessor activities; r_2 refers to the number of second or subsequent releases of the node, when $r_2 = \infty$, it means that the node can only be implemented once, and cannot be released again. n is the sequence number of the node.

After the simulation of Figure 1, if the 5-3 loop is realized, the positive network is obtained as shown in Figure 2. There are 3-5-3-5 duplicate nodes in the network, 7 and 8 numbers are used to replace the later 3-5 nodes, and Figure 3 is obtained. Through calculation, the critical chain is 1-3-5-2-4-7-8-6, with a total construction period of 11 days; If the 5-3 loop is not implemented, the positive network is as shown in Figure 4. Through calculation, the critical chain is 1-3-5-4-6, with a total construction period of 7 days.

Through 100 simulations, the results of each simulation can be counted, and the results of 7-day construction period appear 68 times, and the results of 11-day construction period

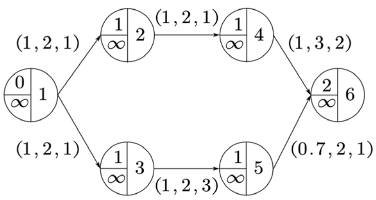


FIGURE 4. The GERT diagram whose feedback loop did not implement.

appear 32 times, so the probability of 7-day completion is 68%, and the probability of 11-day completion is 32%. Therefore, the statistical key chain of the GERTs network diagram is 1-3-5-4-6, and the most likely total construction period is 7 days.

B. PREMISE HYPOTHESIS

To facilitate the study of critical chain identification method in resource-limited GERTs, this paper further idealized the research object, and made the following assumptions for the selected GERTs network plan identification process:

1) In the whole process of project implementation, the total amount of bottleneck resources remains unchanged;
2) The resource usage quantity of any operation is an integer;
3) The operation in execution cannot be interrupted, that is, once any activity in the project enters the execution state, other operations cannot interrupt this operation until the execution of this operation is completed;
4) The node type of the network is assumed to be one or more of "and-determinate", "and-random" and "or-determinate";
5) There is no overlapping relationship between operations, all of which are end-start relationships.

C. STATISTICAL PARAMETER SETTING

1) CRITICALITY CC_I

Criticality refers to the ratio of the frequency of an active link becoming a critical link to the total number of simulations in a GERTs network. In n times of network simulation, one critical chain can be obtained at each time, i.e. L_1, L_2, …, L_n, in which a critical chain may appear repeatedly m times, and CC_i is used to indicate the criticality of the critical chain, following (1).

$$CC_i = \frac{n_i}{N}, \quad i \in [1, 2, \ldots, m], \quad n_i \in [1, 2, \ldots, N], CC_i \in (0, 1) \tag{1}$$

Suppose $CC_j = \max\{CC_i\}$, $j \in [1, 2, \ldots, m]$, then activity linked L_j, which is the most frequent sub-network critical chain in stochastic network simulation, is the critical chain in the statistical sense of the stochastic network. Therefore, the critical chain of stochastic network planning is the activity link with the largest CC_i value.

2) SENSITIVITY OF CRITICAL CHAIN δ

The sensitivity of critical chain indicates the degree of conversion between the critical chain and non-critical chain. Suppose CC' represents the critical chain rate of the activity link next to Max $\{CC_i\}$, that is, this activity link is the subcritical chain of the random network, then follows (2):

$$\delta = CC' / \max\{CC_i\}, \quad 0 \le \delta \le 1 \tag{2}$$

The larger δ is, the more likely the critical chain of the GERT network is to be transformed into the non-critical chain, the higher the sensitivity value of the critical chain is, and the more unstable the critical chain of the random network is. Therefore, in the process of project control, not only the critical chain should be controlled, but also the activities on the subcritical chain should be fully concerned. The smaller δ is, the lower the sensitivity of the critical chain of the GERT network is, the less the possibility of the critical chain conversion is, and the more stable the critical chain is.

IV. CCPSP OPTIMAL SCHEDULING MODEL

A. MODEL ASSUMPTIONS

1) Each activity has a variety of execution modes to choose from. Each execution mode corresponds to different duration and resource requirements. During execution, resources are occupied within the duration. After execution, these resources are released.
2) Each activity can only be executed in one of the execution modes, and once executed, the execution mode cannot be interrupted or changed until it is completed;
3) Activities have timing constraints and resource constraints;
4) Each activity needs fewer resources than the maximum supply of resources;
5) When numbering events and activities, make sure that the events are strictly increasing according to time sequence constraints, that is, the number of all precede events of event i must be less than i, and the number of subsequent events must be greater than i;

B. ABSTRACTIONS OF MATHEMATICAL PROBLEM

In this paper, the GERT network diagram is used to describe the remanufacturing process of waste products. The remanufacturing process of waste products is shown in Figure 5 [14]. The disassembly of waste products is the first step of remanufacturing. The products are disassembled into several parts or functional components; then, according to the test results, the waste parts are divided into direct reuse parts, remanufacturable parts, material recycling parts, and direct waste parts [15]. Direct reuse parts refer to the parts whose shape, size and performance meet the requirements of remanufactured products and can be used directly; remanufacturable parts refer to the parts of normal wear and tear, which can restore their performance and meet the requirements of remanufactured products through remanufacturing; Material recovery parts refer to the parts that are completely

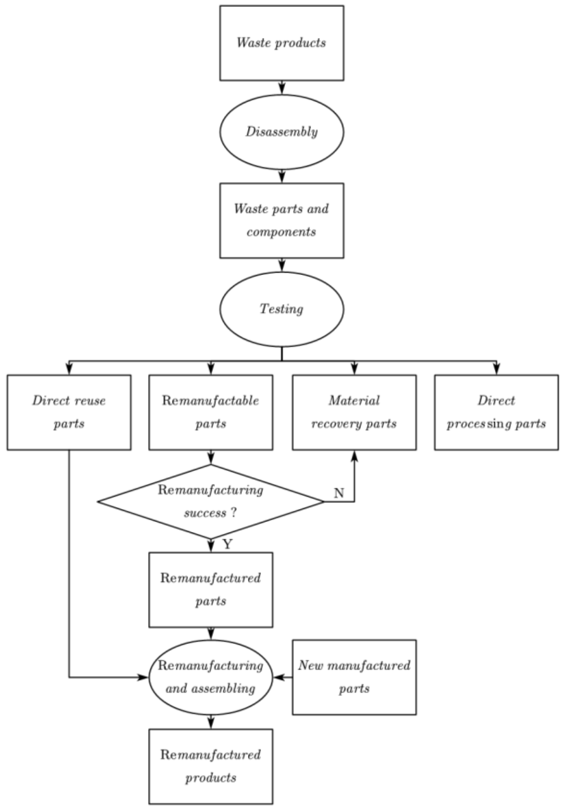


FIGURE 5. Remanufacturing technology process of waste products.

damaged or have low remanufacturability at present, so they are selected for material recovery; Direct waste parts refer to those parts which are limited by the recycling technology of waste parts and the market demand of recycled materials at the same time. The parts cannot be reused or the economic value of material recycling is very low, so they should be directly discarded.

The remanufacturing process can be described as a kind of waste parts to be processed, after cleaning → testing → remanufacturing and other process steps, to meet the requirements of remanufacturing products. However, due to the high uncertainty of the quality of waste parts, the remanufacturing process has many randomnesses. On the one hand, the remanufacturing process generally presents the characteristics of multiple feasible probability branches. Some of the waste parts need to go through all remanufacturing process routes, while most of the waste parts only go through some of them; on the other hand, due to the difference of service time and working condition of the waste parts, the damage degree of the parts is different, which makes the remanufacturing process time uncertain, so it is difficult to make a proper remanufacturing process route. Through GERT, all possible remanufacturing process routes of waste parts can be depicted, process time and process branch probability can be calculated, which can provide support for resource allocation of remanufacturing workshop.

To facilitate the solution to CCPSP, virtual event 0 is introduced as the preceding event of all events without preceding

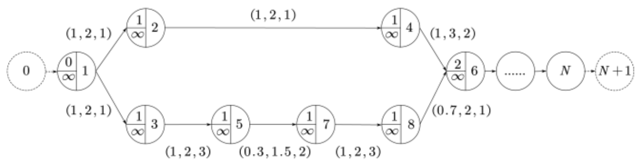


FIGURE 6. GERT network graph with virtual activity.

event, virtual event N+1 is introduced as the follow-up event of the event without follow-up event, and virtual event 0 and virtual event N+1 have only one execution mode, do not occupy resources and execution time as 0, which represents the initial state and end state of the whole project. F_{n+1} is the earliest start time of the unique activity (M+1) corresponding to the end event (N+1), which is the total project duration, as shown in Figure 6.

Therefore, CCPSP can be abstracted into the following mathematical problem: under the resource constraint, the project description is transformed into the GERT network graph, and all activities (edges) are traversed once and only once from virtual event 0 to virtual event N + 1. The goal is to find the shortest time for a complete traversal.

C. MODEL ESTABLISHMENT

In a weighted directed graph used to represent engineering, the vertex is used to represent event i (such as i_0), the directed edge is used to represent activity v (such as $<i_0, i_1>= v_1$), and the weight on the edge is used to represent the duration of the activity. Suppose G = (V, E), V represents the set of project tasks, and E represents the logical precedence relationship between tasks. After the topological sorting algorithm is used to test whether the network has a loop and eliminate the duplicate code, the network plan of a project can be described as follows:

$$G = (V, E), \quad v \in V, (p, q) \in E, \ v = 1, \ldots, n \quad (3)$$

$$C_k \geq 0, \quad k = 1, \ldots, K \quad (4)$$

$$C_{kv} \leq C_k, \quad (5)$$

In formula (3), V represents all activity sets in the project, v represents all activities in the set, where v = 1 and v = n represent the first and last activities of the project respectively, which are virtual and do not use any resources, and the time required for activities is zero; E represents the logical restriction set of activities, p represents the pre-activity of q, and q represents the follow-up activity of p; In formula (4), C_k represents the upper limit of each renewable resource in the project; in formula (5), C_{kv} represents the demand of activity v for resource k, and the demand of any activity in the project for a certain resource shall not exceed its upper limit. The time consumed by each activity is represented by d_v, and the security time is represented by t_v. There is only one execution mode for each activity in the project and it will not stop after the start until the end of execution. After the execution of activity v is completed, its start and end time are represented by s_v and f_v respectively.

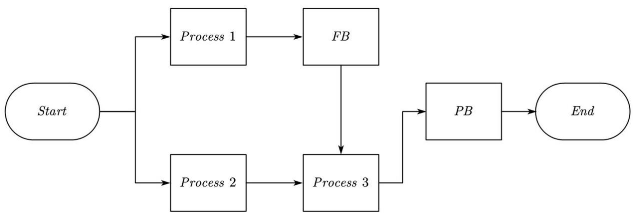


FIGURE 7. CCM scheduling network diagram.

CCM itself is a robust scheduling method. By adding project buffer (PB) in the critical chain tail and feeding buffer (FB) in the non-critical chain tail, the delay risk can be alleviated to a certain extent, and the stability of project implementation can be improved.

Suppose a project contains five tasks, and its network structure of a scheduling plan is shown in Figure 7. It includes a critical chain and a non-critical chain. Task 1 is on the non-critical chain, and the corresponding feeding buffer is FB; task 2 and task 3 are on the critical chain, and the corresponding project buffer is PB. The addition of PB and FB can protect the delay of critical chain and non-critical chain respectively. The addition of FB will also have a potential impact on the start time of task 3.

The sizes of the project buffer and feeding buffer have a direct impact on the robustness of the scheduling plan. Besides, if the consumption of resources fluctuates greatly during the implementation of the scheduling plan, it will not only lead to the intensification of resource demand conflict at the peak of resources, but also lead to the shortage of resource inventory at the low peak of resources, so resource balance should also be one of the influencing factors. According to the above problems and the characteristics of tasks in CCPSP, this paper constructed the robustness "R" to measure the stability of critical chain scheduling, as shown in equation (6):

$$R=\omega_1 \frac{PB}{T_n}+\omega_2 \frac{1}{S}\sum_{s=1}^{S}\frac{FB_s}{p_s}+\omega_3 \frac{1}{K}\sum_{k=1}^{K}\left(\sum_{v\in V_t}\sum_{m=1}^{M}\frac{C_{vmk}x_{vm}}{C_k T_n}\right) \tag{6}$$

From equation (6), it can be seen that the robustness is composed of three parts: the contribution of project buffer to robustness, the contribution of import buffer to robustness, and the contribution of resource consumption to robustness. Specifically, T_n represents the total duration of project buffer, and ω_1, ω_2, and ω_3 are parameters to adjust the robustness of each part, to prevent a part from being too large or too small. PB represents the buffer size of the project, and PB / T_n represents the average allocated buffer size of the project buffer for each day of the project duration. The larger PB / T_n is, the more easily the uncertainty risk of project delays will be absorbed, and the better the robustness of the project will be. FB_s represents the feeding buffer corresponding to the s-th noncritical chain, FB_s / d_s indicates the buffer size allocated by FB_s every day for the total duration of the s-th non-critical chain, then the mean value of FB_s / D_s corresponding to S noncritical chains is calculated, which constitutes the contribution of noncritical chains to the robustness of scheduling. It is obvious that the longer the buffer of the average daily task duration on the noncritical chain is, the better the absorption of uncertain risk. The third part reflects the consideration of the stability of resource consumption, the formula $\sum_{v\in V_t}\sum_{m=1}^{M}\frac{C_{vmk}x_{vm}}{C_k T_n}$ is used to calculate the ratio of total consumption and the total supply of the k-th resource, and then the average value of the k-th resource is calculated. The larger the value is, the more likely the resources are to be fully utilized, the smaller the fluctuation is, and the easier the scheduling plan is to be carried out stably. Finally, by setting the values of the parameters ω_1, ω_2 and ω_3 reasonably, the robustness index to measure the stability of the scheduling plan can be obtained.

This is a typical multi-objective optimization problem, because the shortening of the construction period will lead to the situation that resources are scrambled by various activities, resulting in the decrease of robustness. The objectives of the optimization are to minimize the project duration and maximize the robustness by determining the reasonable execution sequence, corresponding execution mode and start time of activities on the premise of satisfying resource constraints and timing constraints. The corresponding mathematical expressions are:

$$\min(f_n + PB) \tag{7}$$

$$\min(-R) \tag{8}$$

Formula (7) takes the minimum value of the duration index as the first scheduling target of the project, fn is the end time of terminating activity n; PB represents the project buffer on the critical chain, FB represents the project buffer. Equation (8) shows that the maximum value of the robustness index is taken as the second scheduling objective of the project.

The constraints are as follows:

$$s_1 = 0 \tag{9}$$

$$\sum_{m=1}^{M} x_{vm} = 1, x_{vm} \in \{0, 1\} \tag{10}$$

$$s_q - s_p \geq d_p, (p, q) \in E \tag{11}$$

$$\sum_{v\in V}\sum_{p\in V_t} c_{kp}\, x_{vm} \leq C_k, \tag{12}$$

$$FB_{pq} + \sum_{m=1}^{M} x_{pm}\, d_{pm} + s_p \leq s_q, \tag{13}$$

Meaning of the above constraints: formula (9) represents the start time of the project is 0; Constraint (10) indicates that each task can only be implemented in one mode, X_{vm} is a decision variable with only 0 and 1 values; constraint (11) restricts the logical relationship of various activities in the project, that is to say, the subsequent activities can only be started after the execution of the front-end activities; Constraint condition (12) is to constrain the resources of the problem, that is, the sum of all the demands for resource k in the execution activities at time t shall not exceed its upper limit, where V_t represents the task being executed at time t; Constraint (13) indicates that the sequence between the import node and the corresponding critical activity remains unchanged after the import buffer is added.

V. CCPSP PLAN GENERATION SCHEME

The critical chain of solving stochastic network planning is based on the GERT simulation of a stochastic network. The simulation result can be regarded as the process of open-loop processing of the GERT network and obtaining a possible network. Process the resulting network of every GERTs simulation, then solve the critical chain of the resulting network, repeat the simulation process, carry out the statistical calculation, and finally get the critical chain of the GERT network and its related parameters. This paper proposes a CCPSP plan generation scheme to solve the " Duration minimization and robustness maximization" multi-objective resource-constrained project scheduling problem. The scheme flow is shown in Figure 8, and its implementation mainly includes the following seven steps: Random network is transformed into the deterministic network, coding, decoding, computing free time difference, determining critical chain, determining non-critical chain, computing buffer, and embedding buffer. Each step is described in detail below.

A. TRANSFORMING THE RANDOM NETWORK INTO THE DETERMINISTIC NETWORK

1) Carry out a GERTs simulation operation. The corresponding parameters are obtained by the random sampling method. According to the obtained random sampling values, the tight post-processes of random nodes are selected. The branch and loop in a random network are removed and transformed into a network with a definite logical relationship.
2) Adjust the node code of the GERTs simulation result network to eliminate the duplicate code; the unfold of the loop may cause the duplication of work and nodes. To facilitate the follow-up work, the duplicate code in the network is replaced with a new code.

B. CODE

Ant colony algorithm is used to code the activities in the project and generate the activity list. The coding process is as follows:

1) Find alternative follow-up activities that meet the logical constraints and place them in set E. The condition that the activities in set E need to meet is that their precedence activities have been completed.

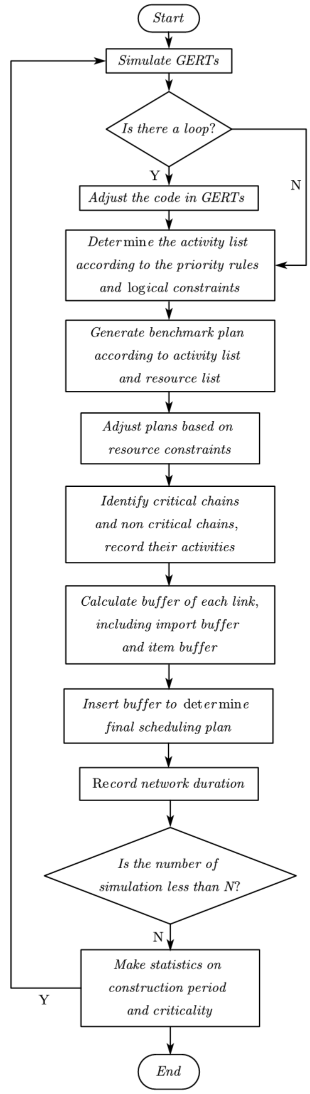


FIGURE 8. CCPSP plan generation scheme.

2) The pheromones and probabilities of all activities in set E are determined by the ant colony algorithm. Pheromone renewal mainly consists of two parts: pheromone volatilization and new pheromone left by ants when they pass by again. The first part is to update the pheromone locally. The ants update the activity after selecting the activity and its pattern. The second part is the elite ant strategy. After all the ants walk, select the ant that consumes the shortest time limit, greatly enhance the pheromone content of the path they walk, so that the next ants have a higher probability to walk from the path.
3) The state transition strategy is the way that ants choose the next path in the list of candidate activities. Determine the next activity to be performed in set E by roulette and put it into the activity linked list.
4) Update the activity wait list. There are two parts to update the activity waiting list. The first part is to delete an activity from the activity list after it is executed.

The second part is that after the subsequent events of an activity were executed, all the precede events of its successor events should be judged. If all the precede events are executed, then add the successor event of the subsequent event of this activity to the activity waiting list.

5) If all tasks are already in the linked list, the coding is completed. Otherwise, repeat steps (1) to (4).

C. DECODE

Arrange activities according to the obtained activity chain list, and determine the earliest start time. The earliest start time to complete an activity must meet the time sequence constraint and resource constraint: time sequence constraint means that the earliest start time of the activity must be greater than the earliest completion time of the subsequent events of the activity; Resource constraint refers to the number of resources in the current resource pool that meet the needs of the activity to be executed. If it does not meet the requirements, it needs to wait for other activities to execute after releasing resources, that is, the current time should be updated to the time when other activities release resources.

D. CALCULATE FREE FLOAT TIME

According to the link plan right shift task determined in step B, get the latest start and end time of each activity. The link plan move right operation needs to be calculated in reverse order from the back to the front. The total duration of the activity remains the same, i.e. the duration of the virtual activity that represents the end remains the same. On the premise of meeting the logical constraints and resource constraints, move its precedence activities to the right, and cycle to the virtual activity that represents the beginning in turn. Finally, the free float time is calculated according to the earliest and latest start time of the earliest and latest end time of each activity.

E. IDENTIFY CRITICAL CHAINS

Activities with zero free time differences are all on the critical chain, but there may be multiple critical chains in the project. Generally, the one with the longest link duration is selected as the final critical chain.

F. IDENTIFY NON CRITICAL CHAINS

All links except the critical chain are regarded as non-critical chain, and the determination method is as follows:

1) Starting from the critical chain, the non-critical activities in the successors of critical activities are found as the starting activities of the non-critical chain.
2) Look backward from the start activity of a non-critical chain. If its successor is not on the critical chain, it is regarded as the activity of this link.
3) Repeat step (2) until it stops after its successor is the activity in the critical chain, and the link ends.
4) Repeat (1) to (3) until all non-critical chains are found, and mark the junction point of the non-critical chain and critical chain for inserting feeding buffer.

G. COMPUTE AND EMBED BUFFERS

The project plans generated by the serial scheduling scheme are all active. In this paper, the serial scheduling scheme for RCPSP is used to generate a positive plan according to the most likely completion time of the task, which is the basis of finding the critical chain. According to the definition of the active plan, no task can move left in an active plan. Therefore, when embedding the input buffer in the generated plan, only the post-task can move right (the start time is pushed back). Embedding the project buffer will not produce new resource conflicts, so it is relatively simple. Embedding the input buffer is more complex because embedding the input buffer will change the task time of the non-critical chain, resulting in new resource conflicts. Here we focus on how to embed the input buffer.

Because it may lead to new resource conflicts, each task move is a complex recursive process. To avoid this computational complexity, all input buffers are added to the project network plan as virtual tasks, i.e. buffer tasks, then carry out secondary scheduling. The duration of the buffer task is set according to the results calculated by the method in [16], which does not occupy any resources, but has a precedence relationship. Its predecessor task is the ending task of a non-critical chain, and its post-task is the critical task corresponding to the non-critical chain. According to the algorithm in Chapter 4, the complete CCPSP project plan can be regenerated.

VI. ALGORITHM OF SOLUTION

A. ALGORITHM DESIGN

In this paper, DEACA (differential evolution ant colony algorithm) is designed to solve the above-mentioned model. Firstly, a one-dimensional real number coding scheme based on the activity execution mode is adopted, and then the activity network diagram is constructed through this coding scheme, after that, a roulette algorithm based on pheromone and heuristics term is defined to realize the state transition strategy. The solution to CCPSP is the process of ants crawling through the graph according to the state transition strategy under the resource and timing constraints. The algorithm improves ant colony by differential evolution algorithm, increases ant's ability to explore other paths and improves pheromone updating rules, such as determining current activity and mode selection according to the mode selected in the previous activity, it effectively overcomes the premature phenomenon of the standard ant colony algorithm in solving the problem, and achieves the effect of fast convergence and the global search for the optimal solution. The implementation process of DEACA algorithm in the model is shown in Figure 9:

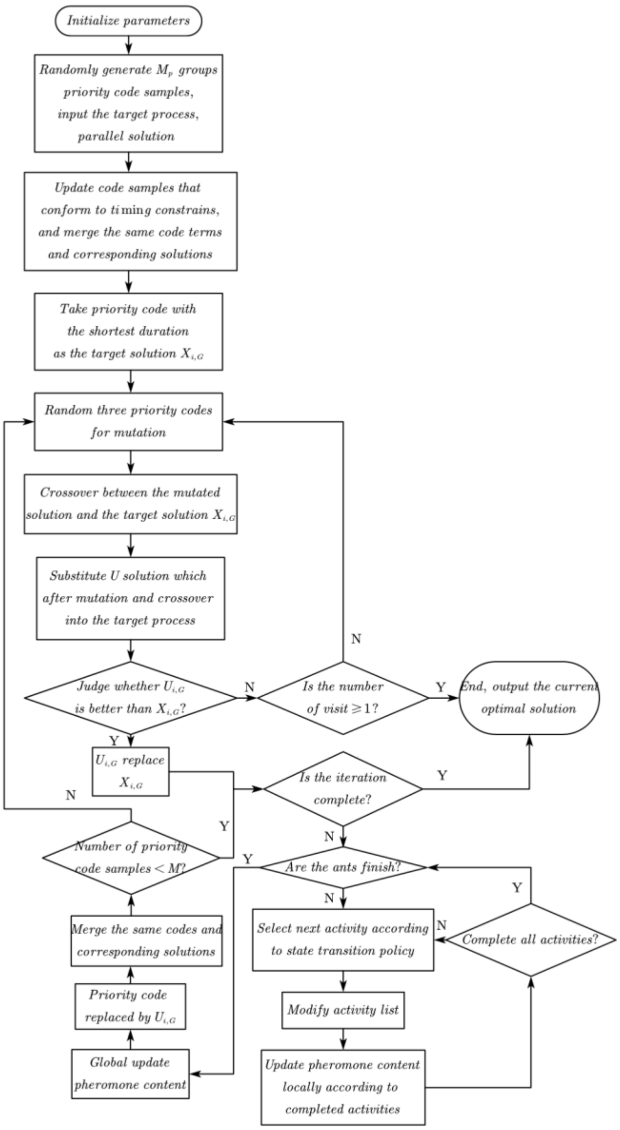


FIGURE 9. DEACA algorithm flowchart.

B. ALGORITHM TEST

For the convenience of illustration, this paper uses a 10 event 14 active project scheduling data set which has been eliminated by a GERTs simulation to verify the feasibility and effectiveness of the DEACA algorithm in solving this kind of problem. Each activity of the project obeys constant distribution and requires three renewable resources R1, R2, and R3. The unit duration limit is 8, 16 and 20 respectively. Except for the corresponding activity of virtual event, each activity in the project has two executable modes: in general mode (N) and compression mode (C) of reducing duration by increasing resources, the duration (T) and required resources of each activity under different execution modes are shown in Table 1.

The optimal total scheduling period of the project is 30 days, and the scheduling scheme is shown in Table 2:

Through the implementation of the algorithm 10 times, the shortest construction period of the project is 30 days, with an average construction period of 31.2 days. The statistical results are shown in Table 3.

It can be seen that the DEACA algorithm can get the optimal solution at the same time, the solution is stable, can

TABLE 1. Specific parameters of each activity in different modes.

Activity	Normal mode(N)		Compression mode(C)	
	Construction period	Resource R1,R2, R3	Construction period	Resource R1,R2,R 3
1	5	(3,2,6)	3	(4,5,8)
2	3	(2,3,4)	2	(3,4,6)
3	6	(3,2,7)	4	(4,4,9)
4	5	(2,3,10)	4	(3,4,12)
5	8	(6,5,5)	6	(8,7,6)
6	5	(2,3,8)	3	(3,4,9)
7	9	(5,4,4)	6	(9,6,6)
8	8	(3,2,6)	6	(5,4,8)
9	10	(7,6,4)	7	(10,8,7)
10	6	(3,2,5)	5	(3,4,6)
11	5	(3,4,8)	3	(4,5,10)
12	4	(2,3,7)	3	(4,4,9)
13	9	(2,3,9)	5	(4,5,10)
14	12	(3,2,10)	8	(5,4,12)

TABLE 2. Optimal project scheduling scheme.

Execution sequence	1 − 3 − 6 − 2 − 7 − 4 − 5 − 10 − 8 − 11 − 14 − 9 − 13 − 12
Execution mode	C − C − C − C − N − N − C − N − N − N − C − C − C − N
Time	0 − 4 − 5 − 5 − 7 − 7 − 13 − 13 − 14 − 19 − 21 − 27 − 30
Critical chain	3-7-11-14

TABLE 3. Running results statistics of ACS algorithm.

Minimum time	Number of times of algorithm
30	3
31	4
32	1
33	2

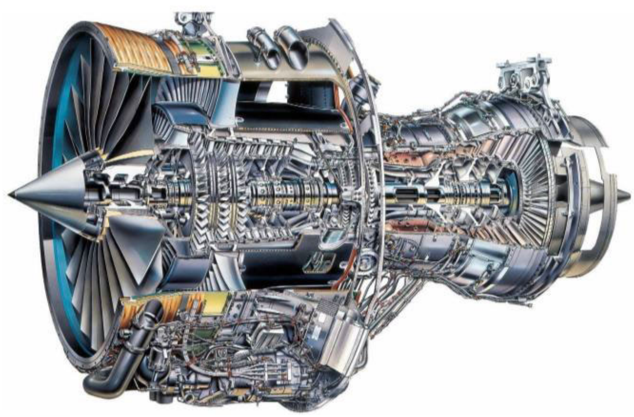


FIGURE 10. Schematic diagram of aeroengine structure (picture source: Baidu Encyclopedia [17]).

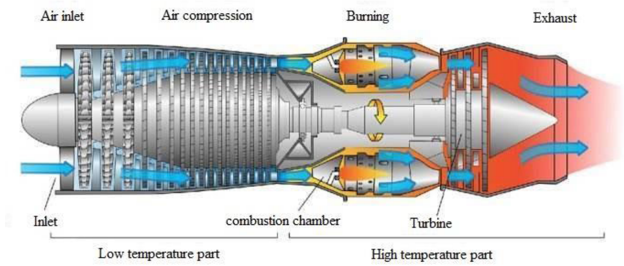


FIGURE 11. Working principle diagram of Aero engine (picture source: Baidu Encyclopedia [18]).

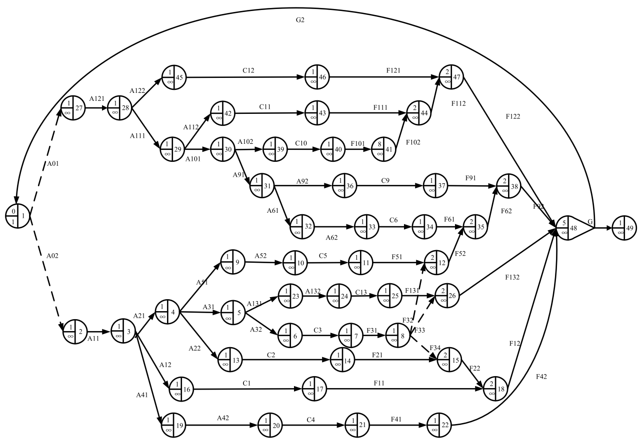


FIGURE 12. First layer GERTs network of V-type aero-engine remanufacturing of company X.

converge globally and the error is only 1.2 days and is not too large, this result can be accepted in engineering application.

VII. CASE ANALYSIS

A. PROJECT BACKGROUND AND DATA

Aero-engine is regarded as the ''heart'' of aircraft, and its reliability is very important to the safe and normal operation of aircraft. There are often events (foreign object damage, FOD) of inhalation of foreign objects (such as sand, birds, tools, etc.) during the operation of aero-engine. The inhaled foreign objects will impact the fan blades and compressor blades under high-speed load, resulting in the damage of notches, tears, pits, etc. of these blades.

As shown in Figure 12, the GERT network describes the remanufacturing process of V-type aero-engine of company X in factory inspection, decomposition, cleaning, fault inspection, repair, final inspection, unit assembly, general assembly, test run, and other steps.

The remanufacturing process of this type of aero-engine consists of three stages, each stage may contain several processes. After the disassembly and cleaning of the first stage, the maintenance sub-network of the second stage is entered. The disassembled parts go through several inspection processes to determine whether the product enters the maintenance operation. The final inspection of the sub-network determines whether to rework.

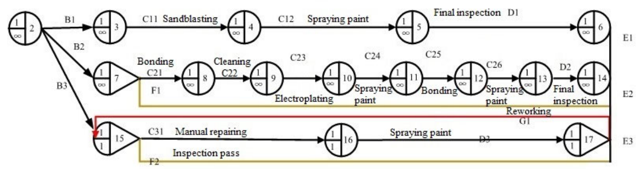


FIGURE 13. GERT network diagram of unit 1 maintenance sub-network.

The third stage is the assembly and assembly of the product. After the different parts of the product have completed their respective maintenance operations, they go through the assembly and combination to enter the final inspection of the product and decide whether the product is a finished product, rework or scrap. The purpose of the simulation model is to estimate the remanufacturing cycle, qualified rate, scrap rate and the lost time of scrap.

The first layer GERTs network of this process is shown in Figure 12. This model has 49 nodes and 60 activities. In each simulation run, as long as the terminal node realized once, it completed one run. Take the A02 branch as an example. At the beginning of the simulation, source node 1 is implemented, activity A02 is a virtual activity, simulation clock starts to move, and random number generator is immediately called to generate the random sampling time specified by activity a11 (according to a normal distribution, for convenience of the solution, rounding is used), and the next node implementation (or event occurrence) time is calculated. When the simulation clock moves to this time, node 3 realizes it. Then the processing time of random sampling is generated according to β distribution, and the realization time of the next three nodes 4, 16 and 19 is calculated.

When the simulation clock reaches the realization time of node 16, it will enter the maintenance sub-network C1 of the first cell (node 2 in Figure 13 corresponds to node 16 in Figure 12, SUB-NETWORK's entry is here), call the evenly distributed random number generator, generate the random number for activity selection, and determine the next activity to be executed. At node 48, if feedback activity G2 is selected, the next event should be node 1 implementation, so the above simulation process is repeated. If the selected activity is G, the simulation enters the end node, thus completing a network simulation. It can be seen from the above that each simulation has only a part of nodes and activity realization, and each simulation has only one end node realization, which reflects the remanufactured products or becomes finished products or scrap products. In the process of simulation, every time a node is implemented, data statistics is done once. When the above processes are simulated N times (for example, n = 500), the random sampling time of each activity in each operation is not the same, and the route of travel is not the same, so the statistical data on each node is a random sample, thus the basic parameters such as sample mean, standard deviation, distribution histogram can be obtained. The counter on the end node can get the number

TABLE 4. Event parameters of maintenance sub-network of unit 1.

Project tasks	Job title	Task start node	Task end node	Distribution mean	Distribution variance	Realization probability	sandblasting	spraying	Bonding	Manual	Milling
A1	Unit 1 disassembly and cleaning	1	2	2.7	0	1	0	0	0	0	0
B1	Failure inspection of fan disk and rear retaining ring of fan blade	2	3	0.1	0	1	0	0	0	0	0
C11	Sandblasting for the back-retaining ring of fan disk and fan blade	3	4	11	18	1	1	0	0	0	0
C12	Painting treatment of rear retaining ring of fan disk and fan blade	4	5	4	10	1	0	1	0	0	0
D1	Final inspection	5	6	2.6	4	1	0	0	0	0	0
E1	Assembly	6	164	0.1	0	1	0	0	0	0	0
B2	Compressor blade filling block fault inspection	2	7	4	9	1	0	0	0	0	0
F1	Inspection pass	7	164	0.1	0	0.2	0	0	0	0	0
C21	Compressor blade block bonding	7	8	5.7	30	0.8	0	0	1	0	0
C22	Compressor blade packing block cleaning	8	9	30.4	26	1	0	0	0	0	0
C23	Electroplating of compressor blade filling block	9	10	0.1	0	1	0	0	0	0	0
C24	Compressor blade filling block painting	10	11	4.8	28	1	0	1	0	0	0
C25	Compressor blade block bonding	11	12	11	30	1	0	0	1	0	0
C26	Compressor blade filling block painting	12	13	5.7	30	1	0	1	0	0	0
D2	Final inspection	13	14	2.6	4	1	0	0	0	0	0
E2	Assembly	14	164	0.1	0	1	0	0	0	0	0
B3	Failure inspection for front retaining ring of fan blade	2	15	3.2	0	1	0	0	0	0	0
F2	Inspection pass	15	164	0.1	0	0.5	0	0	0	0	0
C31	Manual repair of front retaining ring of fan blade	15	16	14	30	0.5	0	0	0	1	0
D3	Final inspection	16	17	1.2	0.4	1	0	0	0	0	0
G1	Rework	17	15	1.2	0.4	0.1	0	0	0	0	0
E3	Assembly	17	164	0.1	0	0.9	0	0	0	0	0

TABLE 5. Computer simulation results of CRITICAL chain identification of the stochastic network.

Average duration / day	Total planned duration / day	Critical chain	Critical chain rate	Critical chain of stochastic network planning	Critical chain sensitivity
97	115	(a)1-2-3-4-9-10-96-97-98-99-100-101-102-164-11-12-35-38-48-49	61.8%	yes	
89	108	(b)1-2-3-16-8-9-10-11-12-13-14-164-17-18-48-49	25.1%	no	
195	212	(c)1-2-3-4-9-10-96-97-98-99-100-101-102-164-11-12-35-38-48-1-2-3-4-9-10-96-97-98-99-100-101-102-164-11-12-35-38-48-49	4.8%	no	
83	104	(d)1-2-3-4-13-36-37-38-39-40-41-164-14-15-18-48-49	3.1%	no	40.6 %
71	94	(e)1-27-28-29-42-149-150-151-152-153-154-164-43-44-47-48-49	2.6%	no	
257	283	(f)1-2-3-4-9-10-96-97-98-99-100-101-102-164-11-12-35-38-48-1-2-3-4-9-10-96-97-98-99-100-101-102-164-11-12-35-38-48-1-2-3-4-9-10-96-97-98-99-100-101-102-164-11-12-35-38-48-49	0.5%	no	
112	130	others	2.1%	no	

of implementations of the node, and thus the probability of its implementation can be calculated. In the sense of practical problems, the probability of the realization of the end node 48 represents the yield of the remanufacturing process, and the corresponding time statistics is the remanufacturing cycle of the product. The statistics on activity G2 show the corresponding repair rate and the distribution of scrap man-hours, etc.

B. SCHEDULE ARRANGEMENT

In this project, there are 25 nodes with uncertain output, and the output probabilities of nodes 7, 19 and 119 are 0.8 and 0.2 respectively; The output probabilities of nodes 23, 95, 131 and 155 are 0.7 and 0.3 respectively; The output probabilities of nodes 49, 103 and 108 are 0.6 and 0.4, respectively; The output probabilities of nodes 15, 29, 35 and 42 are 0.5 and 0.5 respectively; The output probabilities of nodes 17, 64, 79, 87, 92, 127, 148, 154 and 159 are 0.9 and 0.1 respectively; The output probabilities of nodes 91 and 94 are 0.99 and 0.01 respectively; Nodes 17, 79, 91, 94, 119 and 154 each have a ring. The process duration and resource consumption of the project are fixed values. There are five kinds of limited resources, with the upper limit of 4, 2, 4, 19 and 2 respectively. The start time of node 1 is 0, and then it is pushed forward according to the time and logical relationship. The start time as early as possible is used as the starting point of operation execution. There are an incomplete plan, feasible working set and resource set at each time.

When operation I starts, if the number of resources in the resource set can meet the number of resources required by I, the corresponding quantity of resources of I will be deducted from it, when operation I is finished, release the occupied resources to the resource set; If not, wait until an operation is completed and the resource is released, and the resource set meets the operation, then operation I can be started.

When there is a resource conflict between the two processes at the same time, the principle of scheduling is to minimize the impact on the total construction period; When the influence is the same, the process with shorter duration is preferred; If the duration is the same, the operation with smaller node number will be started first.

The simulation results are the nodes of the random network, the start time of each activity, the possible network plan, the corresponding duration and the corresponding frequency of each duration. Because the probability branch implementation of each simulation is carried out randomly, the specific frequency of each operation will be slightly different, but the law shown is the same. The duration of each activity follows a certain probability distribution. When the critical chain is counted, the average of the duration of the critical chain is taken as the average implementation duration of the link. For example, for a certain operation, 1000 simulation times are set, and the results after statistical sorting are shown in Table 5.

According to the result analysis in Table 5, the critical chain of the random network plan of the case project is a critical chain (a), that is, link 1-2-3-4-9-10-96-97-98-99-100-101-102-164-11-12-35-38-48-49, with the corresponding critical chain rate of 61.8%. The most likely average construction period of the project is 97 days, and the total planned construction period is 115 days; The secondary critical chain is the critical chain (b), and the corresponding critical chain rate is 25.1%. Therefore, the critical chain sensitivity of the random network plan is 40.6%. It is necessary to focus on the secondary resource conflict elimination on this link.

Identifying the critical chain of a project is only the first step of the project schedule management method in this paper. A complete critical chain project schedule management method should include the following five steps:

Step 1: identify the critical chain.

Step 2: make full use of the critical chain: reduce the estimated duration of tasks on the critical chain by half to set the project buffer PB, reduce the impact of uncertainty on the critical chain, and shorten the project duration.

Step 3: keep coordination with critical chain: tasks of non-critical chain must be subordinated to critical chain.

① Increase resource buffer and feeding buffer of critical chain;
② Use the above method to solve the new conflict caused by increasing buffer capacity;
③ Review the entire project to ensure that all resource conflicts have been resolved.

Step 4: Improve resource utilization efficiency or introduce new resources to shorten project duration.

Step 5: Go back to the first step and be careful not to let inertia become a new bottleneck.

The above five steps constitute a complete closed-loop project schedule management mode, which ensures that the project can be completed on time within the expected cost in the continuous cycle improvement, and achieves the project output standard. Finally, using the Anylogic 7.0.2 as the simulation platform, according to the identified critical chain, we set up the priority of process using resources, simulated the implementation of the project 100 times, and got the average duration of 101 days, only 4 days of error with the predicted 97 days, which can be accepted in the engineering application.

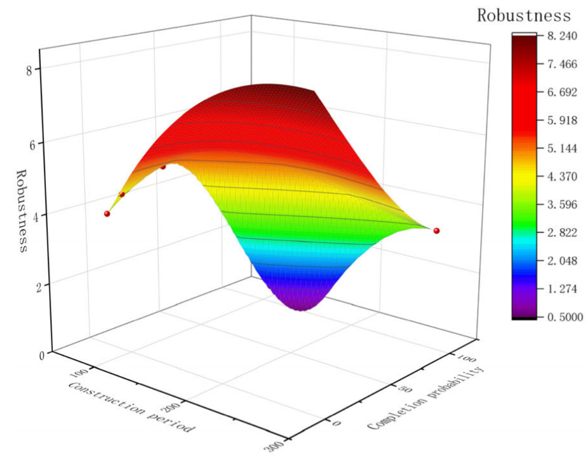


FIGURE 14. **Pareto front 3D surface of construction period, cumulative completion probability and robustness.**

Firstly, this paper identifies the critical chain that constrains the project progress, and reasonably configures the resources and buffers of the critical activities in the critical chain in advance, so as to realize the prediction of the construction period and control the project progress within the expected cost, prevent the project delays, and improve the robustness of the project completion. Finally, the simulation results show that the schedule management method in this paper has a certain predictive effect and practicability in the actual large-scale complex project.

C. APPROXIMATE PARETO FRONT

In order to observe the trade-off relationship more intuitively among the three objectives of construction period, cumulative completion probability and robustness, the 3D surface of Pareto front is fitted as shown in Figure 14.

The marked points in Figure 14 are the corresponding points of each critical chain in table 5. Through observation, it can be found that in the initial stage, with the increase of the total planned duration, the first derivative of the cumulative completion probability increases rapidly and the robustness increases, and the former increases rapidly, when the total planned construction period reaches 115 days, the maximum value of robustness is 8.12, and the cumulative completion probability reaches 95.2%. Then with the continuous increase of the total planned construction period, the robust value decreases rapidly, and the first derivative of cumulative completion probability decreases gradually, which is consistent with the actual situation.

Compared with the feasible solutions in the range of three-dimensional surface and three coordinate planes, the solu-

TABLE 6. Comparison of Pareto set sizes of different algorithms

Algorithm	500 scheduling plans	1000 scheduling plans	2000 scheduling plans
NSGAII	12.25	13.76%	14.31%
ACO	12.23	13.75%	14.30%
DEACA	13.92	14.41%	14.59%

tions on Pareto front are better, because their total time limit is smaller, their robust value is larger, and their cumulative completion probability is higher. The trade-off optimization of duration, robust value and completion probability should be carried out on Pareto front.

D. ALGORITHM COMPARISON ANALYSIS

Suppose that GERT network has n vertices and e edges. When calculating the possible earliest occurrence time and the allowed latest occurrence time of events, as well as the earliest and latest start time of activities, all the vertices in the graph and all the edge nodes in each vertex edge table should be checked. The time spent in the above process is O (n + e), and the time cost of topology sorting is O (n + e). Therefore, the time complexity of the whole algorithm is O (n + e).

For the algorithm evaluation of multi-objective optimization problems, in order to further compare the performance between the algorithm in this paper and the other two different algorithms, 480 test cases of PSPLIB subset J30 are selected as the experimental objects. The size of Pareto set "M", the ratio of non-dominated solution "rate%", and the mutual covering degree "C" between frontier graph and sets [19] are used as the evaluation indexes to compare the performance of the three algorithms. The evaluation indicators are as follows:

1) THE SIZE OF PARETO SET: M

It refers to the number of non-dominated solutions in the set. The more non dominated solutions, the more scheduling options the project can choose, and the better the algorithm can maintain the population diversity. It can be seen from Table 6 that with the increase of scheduling plans, the Pareto set of each algorithm increases, which indicates that the diversity of the algorithm is maintained and the algorithm will not converge prematurely, and DEACA is superior to NSGAII and ACO according to the size comparison of m value, but the difference between NSGAII and ACO is not obvious.

2) THE PROPORTION OF NON-DOMINATED SOLUTIONS: RATE%

It refers to the ratio of the number of solutions that are not dominated by other comparison algorithms in the Pareto set corresponding to an algorithm. The higher the ratio, the higher the Pareto solution level of this algorithm.

From the proportion of non-dominated solution, DEACA is better than the other two algorithms, while NSGAII is slightly better than ACO. DEACA's non dominated solution

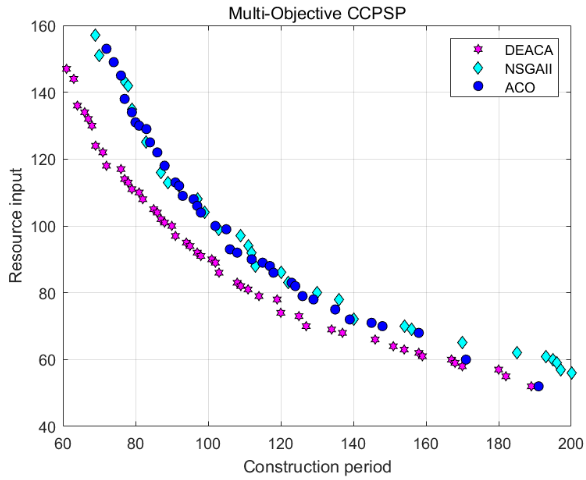


FIGURE 15. Pareto frontier when problem scale reaches 60.

TABLE 7. The proportion of non-dominated solutions of different algorithms.

Algorithm	500 scheduling plans	1000 scheduling plans	2000 scheduling plans
NSGAII	8.11%	9.18%	8.23%
ACO	0.40%	0.19%	0.13%
DEACA	97.24%	91.16%	96.47%

TABLE 8. Comparison results of solution set coverage of each algorithm.

Coverage C（A, B)	Number of iterations 50	100	200	500
C（ACO, NSGAII)	0.40	0.25	0.18	0
C（ACO, DEACA)	0.24	0.06	0	0
C（NSGAII, ACO)	0.62	0.80	0.91	0.76
C（NSGAII, DEACA)	0.33	0.25	0.86	0.42
C（DEACA, ACO)	0.92	1	1	1
C（DEACA, NSGAII)	0.80	0.96	1	1

has a dominant position, and the level of the non-dominated solution is higher.

3) PARETO FRONT

It is the graphical representation of non-dominated solution in Pareto set. It can intuitively see the dominated situation of solutions among each algorithm and the distribution characteristics of solutions. From PSPLIB test set [20], test question j6045_is randomly selected, which has 60 activities and 4 limited resources. The numbers of algorithms iterations are set to 100, and the unit resource fluctuation cost C is set to 1.

Figure 15 is the Pareto frontier graph generated by DEACA, NSGAII and ACO when 1000 scheduling plans are generated as the termination conditions. It can be seen from the figure that the Pareto solution to DEACA has an obvious dominant position. This shows that the performance of DEACA's set of non-dominated solutions is better under the same number of iterations, and its Pareto front can move quickly to the direction of the optimal solution. The solution distribution of ACO and NSGAII is cross, the non-dominated solution to ACO is slightly better than that of NSGAII when the construction period is shorter, and the solution presents the opposite state when the construction period is longer.

4) THE MUTUAL COVERAGE DEGREE BETWEEN SOLUTION SETS: C

It is used to compare the mutual domination relation between Pareto optimal solution generated by the algorithm in this paper and other two algorithms. The specific definition is as follows:

$$C(X_1, X_2) = \frac{\left|\left\{a'' \in X_2; \exists a' \in X_1 : a' \geq a''\right\}\right|}{|X_2|} \tag{14}$$

In formula (14), X_1 and X_2 represent two different Pareto solution sets, and C (X_1, X_2) represents a proportion, which is the number of solutions dominated by X_1 in solution set X_2 divided by the number of solutions in the whole solution set X_2. Its size is between [0,1]. C (X_1, X_2) = 1 means that all solutions in X_2 can find solutions in X_1 that dominate or equal to itself. On the contrary, if C (X_1, X_2) = 0, then any solution in X_2 is not dominated by the solution in X_1. Through this way of comparison, we can clearly see the dominant relationship between the solutions to different algorithms, that is, the advantages and disadvantages of the algorithms. It should be noted that both C (x1, x2) and C (X2, x1) need to be considered, and the sum of C (x1, x2) and C (X2, x1) does not necessarily equal 1.

It can be seen from Table 8 that, with the increase of the number of iterations, the set of non-dominated solutions obtained by DEACA can basically cover the set of non-dominated solutions generated by the other two algorithms NSGAII and ACO. For example, when the number of iterations is 500, C (DEACA, ACO) = 1, which means that all the solutions generated by ACO algorithm are dominated by the solutions generated by DEACA. Meanwhile, C (ACO, DEACA) = 0 indicates that the solutions generated by DEACA are not dominated by any solutions generated by ACO.

To sum up, for multi-objective resource constrained project scheduling problem, under the same environment and termination conditions, DEACA proposed in this paper has better performance than other classical methods.

VIII. CONCLUSION

Based on the critical chain project schedule management method, this paper improved and supplemented the critical chain method from three aspects: multi-objective optimization, combination of critical chain and robustness, and integration of critical chain and GERT theory. In this paper, GERT network was used to describe the remanufacturing process of complex equipment, in order to minimize the project completion time and maximize the robustness, a mathematical model was established, a heuristic algorithm was used to identify the critical chain of complex projects, and a neighborhood structure based on the resources required by the activities in the critical chain was proposed, which reduced the invalid search of the algorithm. A hybrid intelligent optimization algorithm combining differential evolution algorithm and ant colony algorithm is designed to optimize the objective function. When the neighborhood was not exchangeable, the heuristic algorithm was used again to identify the current critical chain, and generated a new initial solution, which reduced the dependence of the algorithm on the initial solution and improved the solution quality of the algorithm. 480 test cases of PSPLIB subset J30 and an actual production project were tested to verify the effectiveness of the algorithm, which provided a feasible and effective method for scheduling complex projects such as multi resource constrained projects using critical chain.

In terms of the improvement of the critical chain method, there are two deficiencies that have not been solved in this paper: (1) Input buffer does not necessarily absorb the delay of non-critical activities. (2) This paper does not realize the cooperation between feeding buffer and project buffer in dynamic environment.

The research work of this paper hopes to play a reference role for the scholars and practitioners engaged in the project schedule management research, and provide an expanding idea for the further development and promotion of project schedule management methods.

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