IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.DOI

Construction of Multi-project Network Planning based on BOM and its Resource Leveling

LIHONG QIAO[1], (Fellow, IEEE), ZHENWEI ZHANG[2], AND ZHICHENG HUANG, JR.[3], (Member, IEEE)

[1]School of Mechanical Engineering and Automation, Beihang University, Beijing, China (e-mail: lhqiao@buaa.edu.cn)
[2]School of Mechanical Engineering and Automation, Beihang University, Beijing, China (e-mail: rotos@163.com)
[3]School of Mechanical Engineering and Automation, Beihang University, Beijing, China

Corresponding author: Zhenwei Zhang (e-mail: rotos@163.com).

This work is supported by the National Key Research and Development Program of China (Grant 2018YFB1701800). The authors also acknowledge the assistance of Beijing Municipal Education Commission.

ABSTRACT For the manufacturing project of large and complex equipment, due to the large number of activities, and the complex structure of the project, there are often cases where multiple projects are going on at the same time, which might make the project's network planning extremely difficult. Based on the analysis of the BOM and classification characteristics of complex manufacturing equipment, this paper proposed an innovative method, which can decompose and transform the component units based on the BOM, so that the BOM of the complex project can be hierarchically optimized and simplified. Then it can be transformed into project network plan by Petri net unit transformation method, so as to realize the decomposition and arrangement of multiple project plans. On this basis, aiming at the problem of resource leveling in multi-project planning management, this paper proposes a genetic algorithm, which provides a transformation method for resource optimization. In addition, this paper presents a new genetic coding method and improves the crossover operation. Case study shows that the algorithm can solve the resource balance problem of multi-project planning successfully. Finally, in order to verify the effectiveness of the algorithm, the proposed algorithm is compared with the other two algorithms intuitively and quantitatively.

INDEX TERMS BOM, Petri net, multi-project, network plan, resource leveling, genetic algorithm

I. INTRODUCTION

NETWORK planning is a planning method of project management, and it is the theoretical basis of project planning. For the manufacturing project of large and complex equipment, such as aircraft, ships, weapon systems and other large-scale equipment, the complex composition structure as well as the large number of components of this kind of equipment make the manufacturing and assembly process extremely complex. In a project cycle, it is necessary to complete the procurement of materials, the production of parts and components, the assembly of components, and the debugging of products. The manufacturing of complex equipment consists of a large number of activities, and there are complex relationships to the production activities, resulting in a huge project network, and the complex correlations between multiple layers of the network also need to be handled, all these make the project planning extremely difficult. The complicated relationship between them makes the project network plan extremely difficult. At the same time, unreasonable network plan will lead to a lot of reworking, which will lead to increased production costs, project overdue and other issues. In addition, in the actual production of equipment manufacturing enterprises, there are often multiple projects in different stages carried out at the same time. When multiple projects are carried out at the same time, conflicts often occur between projects in various aspects such as product matching, resource sharing, and schedule arrangement. This makes the project planning extremely complicated. For the project plan of complex equipments, how to make an effective network plan is the key to the smooth implementation of the project activities. For the multi-project planning problem of complex equipment products, this paper puts forward a unique solution from two aspects: complex project planning and resource balance optimization.

For the research of project network plan, there are mainly methods of network plan decomposition, network planning modeling and optimization, and so on. The decomposition methods of network plan have been studied earlier, mainly including hierarchical decomposition methods and component decomposition methods. These methods have a simple decomposition process, but sometimes they cannot be carried out in actual applications, and they will encounter the problem of too many network layers. In addition, the relationship between the main and sub networks also need to be handled separately. In the study of the network plan model, Su et al. [1] proposed an extended CPM (Critical Path Method) network, which is used to simplify the complex active network of GPRs (Generalized Precedence Relations). Nakade et al. [2] discussed the theoretical meaning of the known indices by using a two-value activity stochastic PERT (Program Evaluation and Review Technique) network and proposed new indices on measurement of activities. Bozhenyuk et al. [3] proposed a graph-based approach to modelling and solving combinatorial resource-constrained scheduling problem, then operated on one single activity mode to construct a schedule. Zhang et al. [4] established a weighted complex network to systematically express the structure of complex mechanical products and proposed a community detection algorithm to achieve the module partition of complex mechanical products.

Other methods have been proposed to solve network planning problems. Li et al. [5] analyzed the influence of time switching constraints and learning effects on the project network, and established a project network model with time switching constraints, through which it could be realized changes to duration and critical path. Mourad et al. [6] studied the problem of dynamic key node detection and dynamic key link detection in random networks, and provided an effective algorithm to determine key nodes. Joost et al. [7] contributed a parametric critical path algorithm, which can identify bottlenecks based on the underlying causes of constraints.Yaghoubi et al. [8] studied the problem of resource allocation in multi-class dynamic PERT networks with finite capacity of concurrent projects. The dynamic pert network was modeled as a queuing network and different types of new projects were generated based on independent Poisson processes with different rates over the time horizon. Nakade et al. [9] discussed the measurement indicators of activities using a binary activity stochastic PERT network, and proposed new indicators of the importance of activities.

For multi-project resource optimization, Creemers et al. [10] presented an exact model that uses a backward SDP (Stochastic Dynamic-programming) recursion to determine the minimum makespan of the project, and acyclic PH (Phase Type) distributions were used to model activity durations. Adhau et al. [11] proposed a DMAS (Distributed Multi-agent System) using auctions based negotiation approach for the resource intervals and allocating multiple different types of shared resources amongst multiple competing projects. Based on MAS (Multi-agent System), Wauters et al. [12] introduced a learning-based optimization approach to solve the resource constrained multi-project scheduling problem, and built a multi-project schedule by using a serial schedule generation procedure. Lu et al. [13] presented a resource constrained multi-project scheduling problem based on project splitting, and established an integrating optimization mathematical model to make decisions on project splitting and project scheduling simultaneously.

Heuristic methods have been used to solve multi-project scheduling problems. Meloni et al. [14] studied the evaluation of the expected shortfall or the conditional value-at-risk for the makespan in scheduling problems, and proposed lower and upper bounds heuristics and an exact method of a class of activity networks. for the resource leveling problem with MRLP-GPR (Multiple modes and Mode-dependent GPRs). Li et al. [15] proposed several heuristics which are competitive with three baseline heuristics. For the preemptive multi-project scheduling problem with activity splitting, Wang et al. [16] proposed three heuristic rules for the activity splitting judgment.

Branch and bound algorithm are also used in multi-project scheduling problems. Rostami et al. [17] proposed a branch and bound algorithm and an improved competitive genetic algorithm for large-scale and multiple resource-constrained project scheduling problem. Ponz-Tienda et al. [18] proposed a parallel branch and bound solution algorithm was proposed to solve the RLP (Resource Leveling Problem) with minimal lags, which realized the optimization of resource activity under the resource leveling. Damci et al. José et al. [19] developed a branch-and-bound procedure for the resource-constrained project scheduling problem, and a composite lower bound strategy that statically and dynamically selects the best performing bounds is used to find optimal solutions.

Other methods have also been proposed to multi-project scheduling problems. Geiger et al. [20] studied t the multi-mode, resource-constrained multi-project scheduling problem, and developed a solution based on the concepts of variable neighborhood searchs, together for iterated local searchs. For solving the resource constrained project scheduling problem with stochastic durations, Cui et al. [21] proposed a two-stage integrated optimization algorithm to generate robust project schedules against disruptions. Azami et al. [22] investigated a complex two-stage hybrid flow shop scheduling problem, propose a discrete-time mixed integer linear programming model with an underlying branch and bound algorithm. Wang et al. [23] studied the resourceconstrained project scheduling problem with a single shared resource and proposed a column-generation-based algorithm.

Genetic Algorithm has frequently been used for multi-project scheduling problems. Okada et al. [24] presented a new genetic algorithm and two new local search methods. The local search ability was improved by reducing the critical path, and the resource allocation ability was improved by ifbLS (iterative forward/backward Local Search). Jin et al. [25] proposed a MOMA (Multi-objective Memetic Algorithm) to solve integrated process planning and scheduling, which combines a VNS (Variable Neighborhood Search) procedure and an effective objective-specific intensification search method. Amiri et al. [26] studied the balance of the cost and time parameters in managing construction projects including resource constraints, and developed a non-dominated sorting genetic algorithm method. Wang et al. [27] studied the RCPSP (Resource Constraint Project Scheduling Problem) with minimization of the makespan, the total job tardiness and maximization of the workload balance level, Non-dominated Sorting Genetic Algorithm, and applied non-dominated sorting genetic algorithm to find approximated Pareto fronts. Yu et al. [28] built an optimization model on resource-constrained project scheduling for overlapping activities, and An improved genetic algorithm based on priority rules and schedule generation mechanism with overlapping is given. Damci et al. [29] studied the impact on different objective functions as resource leveling with Line-of-Balance scheduling methodology, and realized the allocation of resources through a genetic algorithm-based model; Chu et al. [30] solved the multi-mode resource constrained project scheduling problem with activity overlapping, an optimization model is proposed. The relationship between overlapping and rework is described by a time factor matrix, and the model is solved by an improved genetic algorithm based on specific schedule generation mechanism. Yazdani et al. [31] presented a MODRCFJSP (Multi-objective Dual-resource Constrained Flexible Job-shop) scheduling problem, and proposed two types of multi-objective genetic algorithms.

At present, the study on project network plan mostly focuses on the planning model and its optimal solution. This kind of method is mainly based on the decomposition, level transformation and processing of network plan itself to make multi-level network plan. This method is suitable for small project network plan. However, for large complex assembly project, because of the complexity of composition structure and connection relationship, the decomposition and transformation of network plan very difficult. In the research of traditional network planning, the researches on the relationship between project network plan and BOM are less. For the researches on the project resource leveling problem, most of them focus on single project and multitype resource allocation, but few on multi-project resource leveling. The main contribution of this paper includes the following three aspects: first, this paper studies the BOM of complex projects and their production characteristics, and proposes a BOM conversion method based on component unit decomposition to realize the simplification of complex projects; second, this paper proposes a mapping method from project BOM to Petri net process model, so as to realize the creation of the project network plan based on the Petri net model; third, this paper proposes a new optimization algorithm that can be used for the resource balance of the above-mentioned complex project, and gives a calculation example and a comparison of the optimization results., and also the results are compared with those of PSO and ACO.

The main content of this paper includes six sections, from section 2 to section 7. In Section 2, we propose the BOM conversion method based on component unit decomposition, and in Section 3, we further propose using Petri net method to construct multi project network plan. In Section 4, we give the mathematical model of resource balance of multi project network plan, and in Section 5, we describe the design of the algorithm. The content of the experimental verification of the algorithm is in Section 6. In this section, we make an example analysis, and compare the algorithm with particle swarm optimization and ant colony algorithm. The last section is the conclusion, which summarizes and prospects the research results of this paper.

II. BOM CONVERSION METHOD BASED ON COMPONENT UNIT DECOMPOSITION

For the project plan of complex equipment, the traditional planning method is to prepare annual project plan by planning department, formulate several milestone nodes, distribute them to production department, and production department will refine to monthly plan according to milestone node, and production team will then divide into specific production and manufacturing activities to parts according to monthly plan. The decomposition of this plan mainly depends on the experience of personnel. The arrangement of planned activities and resource allocation are random, which leads to the disjointed arrangement of the plan from the actual implementation, and the progress of the activities is easy to delay. When multiple projects are carried out at the same time, these problems are more frequent. In this paper, a new method of cell component decomposition and conversion is proposed by studying the product BOM of complex equipment project, which makes the automatic decomposition of large-scale complex project plan possible. In addition, the transformation from the decomposition model of unit components to Petri net is realized. The project network plan can be described, analyzed and solved by using the theory and mathematical model of Petri net . Thus, the project network plan formed has better mathematical theoretical support than the traditional network planning method. The decomposition and transformation method of component unit proposed in this paper is an innovative method.

As the basic data of a product, BOM plays an important role in connecting product design and manufacturing. BOM not only indicates the composition relationship between components at various levels, but also the basis of material matching in production. For the manufacturing of the complex equipment, its network plan is a list of all production activities implemented by the project, and its construction requires the BOM as the information support. The arrangement of production activities is closely related to the product BOM. The BOM is a key element in the implementation of its various activities. The decomposition of the project network plan is constrained by the relationship between the composition of the project products and the planned tasks. In order to build a network plan for a complex equipment manufacturing project quickly and effectively, this paper

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3078840, IEEE Access

attempts to use BOM as an important information source of its network plan construction. The production activities can be divided according to its product BOM. Through the classification and definition of product BOM, and then carry out decomposition, conversion and simplification, finally, a simplified BOM can be formed, according to which the project network plan can be built. This method can effectively reduce the complexity of project planning while maintaining the activity correlation, and provides a feasible solution to the production plan of complex equipment manufacturing project.

For the initial BOM of the project product, its structure can be defined with a two-tuple:

$$X = (D, A, T)$$

D is the set of product nodes, $D = \{d_i\}$, i=1,2...,n; n is the total number of nodes in the BOM d_i is the i-th node of the product; A is the relationship between the nodes, $A = \{d_i, d_{ij}, q_{ij}\}$, i=1,2...,n, j=1,2...,m; m is the number of the child nodes of d_i; d_{ij} is a child node of node d_i; q_{ij} is the number of node d_{ij}; T is the duration set of the nodes; t_i represents the duration of the node d_i.

For the above product structure, it can be divided according to the characteristics of the production process, and the nodes in the BOM are divided into two categories: classified nodes and unclassified nodes. Classified nodes are nodes that can form independent activities. These nodes belong to the activities that need self-made. Unclassified nodes do not constitute independent activity units, and they can be either self-made activity nodes or outsourced activity nodes. Outsourced activities can centrally or in advance release the purchase plan, and there are fewer restrictions on resources, so its plan arrangement is relatively loose. The classified nodes are the activity nodes that need self-made, so they need strict plan arrangement due to the limitation of internal resources. Classified nodes can be further divided into integration nodes and product nodes. Integration nodes are oriented to the assembly production. Product nodes are the smallest activity nodes and cannot be subdivided. The integration and product nodes can be further divided according to the category and technical requirements of the project.

According to the above classification, the nodes of the initial BOM of the product can be marked, including the product category and serial number of the node, and the marked BOM can be recorded as:

$$X_1 = (J, P, N, A, T)$$

J is the set of integration nodes; P is the set of product nodes; N is the set of unclassified nodes; $D = J \cup P \cup N$. Classification and marking of BOM component nodes need to follow the following four principles:

1) All markings are performed according to the basic decomposition units, which include 1st class and 2nd class decomposition units. As shown in Fig.1, the 1st class decomposition unit can be used in all decomposition processes.
2) For a J-type node, it should be consisting of no less than two child nodes. The child nodes may be J-type nodes, P-type nodes, or N-type nodes, but it is not allowed that all its child nodes are N-type nodes.
3) For P-type nodes, it can only be decomposed once at most, and it can be decomposed into multiple N-type nodes. If it is a leaf node, further decomposition is not allowed.
4) For the decomposition of nodes, let the set consisting of all superior nodes of this node be M. If M contains J-type nodes, the N-type nodes can be decomposed according to the 2nd class decomposition units without violating principle (2). If M is empty or M does not contain a J-type node, the N-type nodes can only be decomposed according to the 1st class decomposition units.

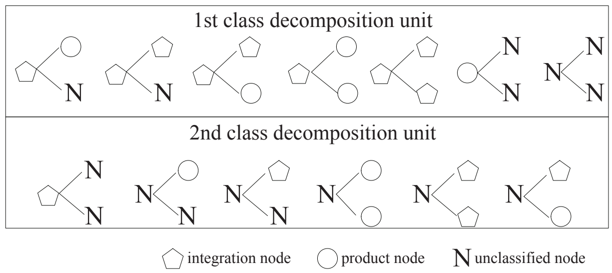


FIGURE 1. Basic decomposition unit of BOM component

Fig.2 shows an example of the BOM decomposition according to the above principles. In this figure, the decomposition on the left is wrong, while the right is correct.

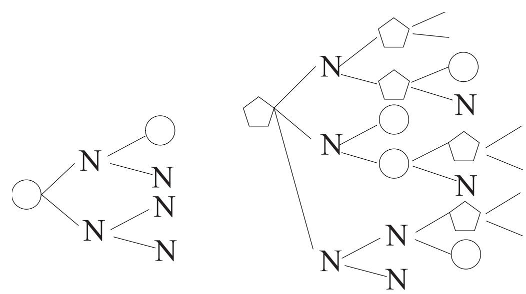
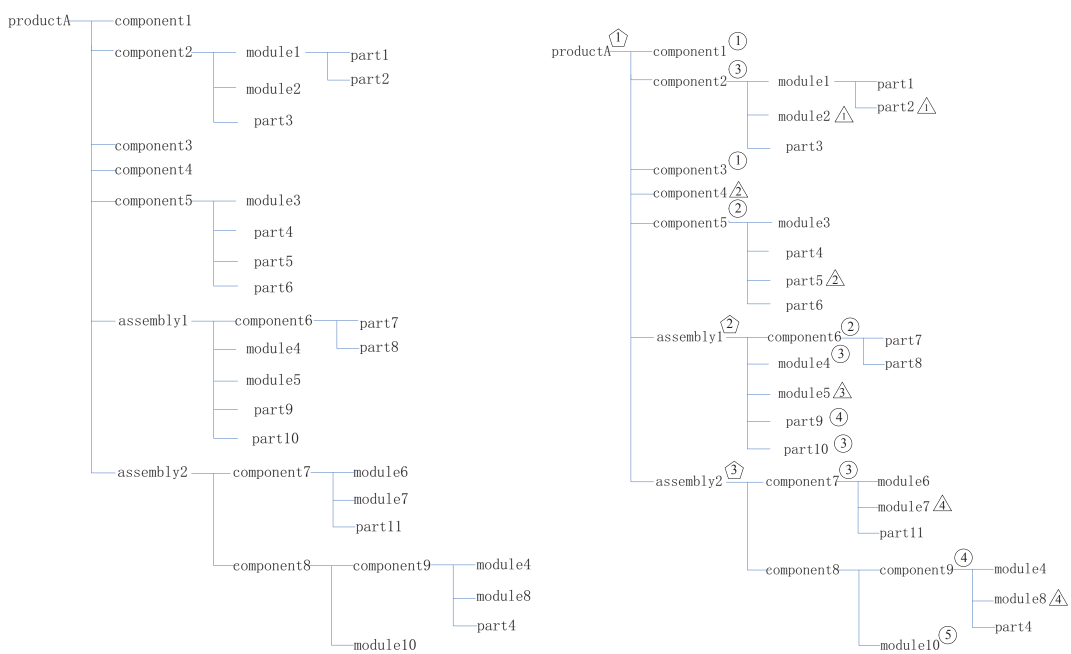


FIGURE 2. An example for BOM decomposition

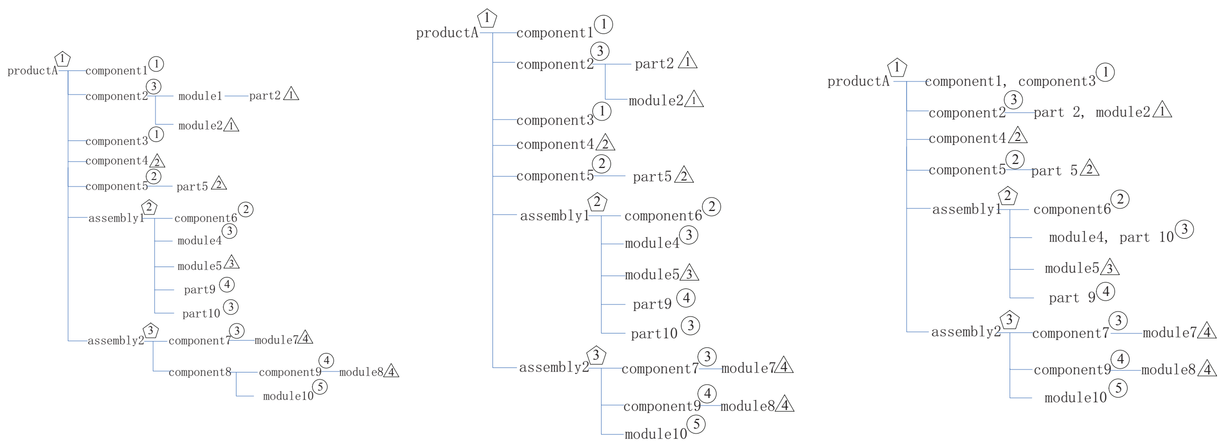
According to the above decomposition principles, we can mark product A as shown in Fig.3. Fig.3 (a) is the initial BOM, and Fig.3 (b) is the marked product BOM. The Δ symbol represents a N-type node of an important outsourcing activity, and the plan of these nodes can be arranged in advance. Unmarked nodes are other N-type nodes, and these nodes are not sensitive to the plan arrangement, such as the outsourcing activity or a simple assembly activity of a standard product. The marked sequence number can be repeated. If the sequence number of the same node is the same, the tasks can be arranged at the same time.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3078840, IEEE Access



(a) Initial BOM (b) Marked BOM

FIGURE 3. BOM marked according to the decomposition principle



(a) (b) (c)

FIGURE 4. BOM components simplification

After the BOM is marked, further simplification is needed. Various types of nodes of the marked BOM can be simplified according to their importance to the project, especially the simplification of the N-type nodes. The simplified process is as follows:

1) For an N-type node, if it is a leaf node or its subordinate nodes are not marked, the node can be removed, as shown in Fig.4 (a).
2) Remove other unmarked N-type nodes and connect their immediately preceding nodes to their succeeding nodes directly, as shown in Fig.4 (b).
3) Merge the nodes that belong to the same parent and have the same mark symbol, as shown in Fig.4 (c).

After simplifying the marked BOM according to the above steps, a new BOM will be formed, which can be represented by a new two-tuple:

$$X_2 = (D', A', T')$$

D' is the node set of the new BOM, $D' = \{d'_r\}$, r=1,2...,k, $D' \in D$, $D' = (J', P', N')$. J' is the set of Integration nodes of the new BOM; P' is the set of product nodes of the new BOM; N' is the set of unclassified nodes of the new BOM; A' is the new relationship between the nodes, $A' = \{d'_r, d'_{rs}, q'_{rs}\}$, r=1,2...,k, s=1,2...,l, k represents the

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3078840, IEEE Access

number of the child nodes of d'_r, d'_{rs} is a child node of the node d'_r, q'_{rs} is the number of the node d'_{rs}; $T'$is the duration set of the nodes; t'_r represents the duration of the node d'_r.

Remark 1: The above method provides a BOM conversion method for complex projects. Through conversion, the product BOM can be converted into a project BOM focusing on task planning. At the same time, the complex BOM is simplified based on the component decomposition rules. The conversion method is not limited by the complexity of the project and the BOM hierarchic structure, and can be used to simplify the BOM of the complex equipment projects and create their network plans.

III. PROJECT NETWORK PLAN GENERATION BASED ON PETRI NET

For the traditional project planning methods, such as CPM, it is necessary to assume that the time of each activity is determined, which makes the project plan lack of dynamic analysis ability. PERT can use the network diagram to make the project schedule, but it needs to accurately estimate the time and resources required by each activity in advance, which makes the predicted duration deviate from the actual situation. Petri net is a kind of combination model with graphical expression, which has strict mathematical definition and normative semantics. The analysis of Petri net is supported by mature mathematical model, which can be used for both static structure analysis and dynamic process analysis.

BOM represents the structure view of the product, which cannot be transformed into the schedule of the project. However, Petri net represents the process view, so we can get the network plan of the project by mapping the BOM product structure model to the Petri process model. Petri net model can be described by a triple:

$$< P, T, F >$$

P represents the set of place, which indicates the state of the activity, such as whether the activity is ready or not; T represents the set of transition, which indicates the change of activity state, such as the development process of the activity; F represents the directed arc set between the place and the transition, which indicates the flow direction of the resource.

The mapping of product BOM to Petri net is shown in Figure 5, and the implementation of this method is as follows:

1) Traverse the BOM to identify its leaf nodes and component nodes;
2) For leaf nodes or component nodes with only one child node, they can be represented by a group of Petri cells, each containing a place and a transition;
3) For the component node with more than one sub node, it can be represented by two groups of Petri cells, which represent the preparatory work and production work respectively, and each group of cells contains a place and a transition;
4) According to the node relationship of BOM, the relationship among the elements of Petri net can be formed;
5) The output place P_e is added to the generated Petri net, and the end transition and P_e are connected to form a complete Petri net plan view.

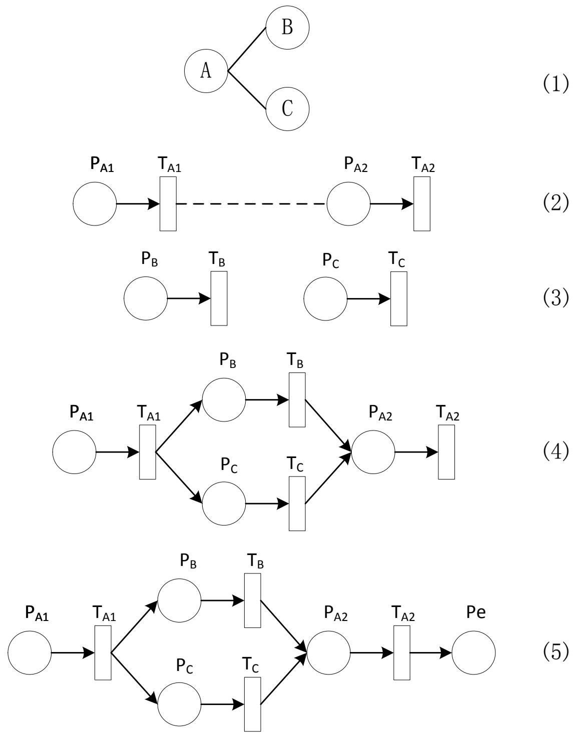


FIGURE 5. Mapping from BOM to Petri net

For the new BOM formed after decomposition, transformation and simplification in the above example, the project network plan based on Petri net can be generated according to the mapping method from BOM to Petri net. The transformation from product A to Petri network plan is shown in Figure 6.

The above conversion from project BOM to Petri network plan is for a single project. In the case of multiple projects, each project needs to be converted separately according to its BOM, and then the following operations can be carried out according to the relationship between them: if the projects are independent of each other and do not affect each other, they can be merged according to the parallel project plan. By adding input place, transition and output place, and make the input and output nodes of the original project point to the new input and output nodes. If the projects are related to each other, the same kind of Petri cells can be merged, and then they can be processed according to the transformation method of parallel projects.

Through the mapping from BOM to Petri net, the product structure view is transformed into project planning process view, and each element in BOM is decomposed according to project planning. Through the flow of token in Petri net, we

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3078840, IEEE Access

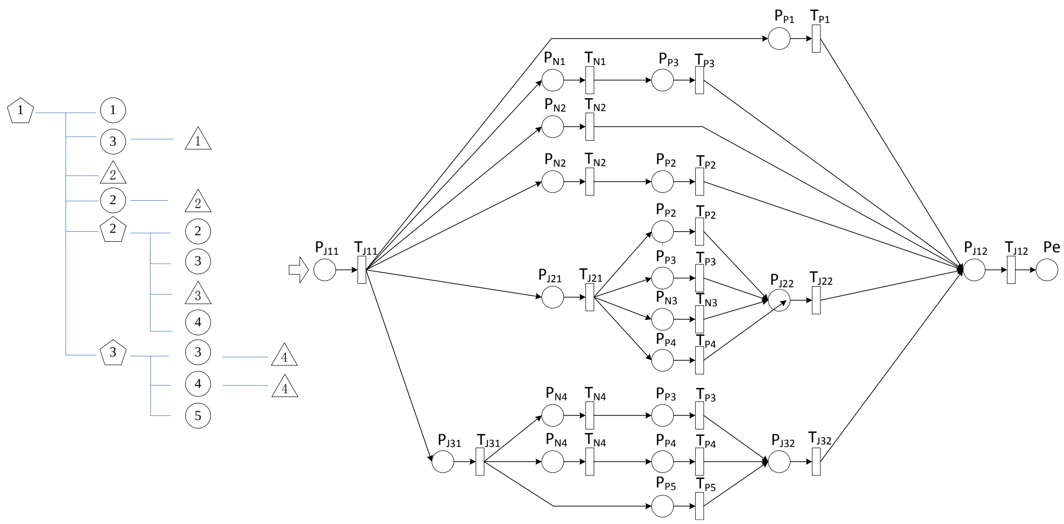


FIGURE 6. Transformation from BOM to Petri network plan

can simulate the dynamic change of project running; at the same time, we can use Petri net to establish state equation, algebraic equation or other mathematical models to analyze the run process of the project. According to the Petri net mapping algorithm, we can calculate the relationship between project activities and the start and end time of activities, so as to obtain a complete project network plan with time planning.

Remark 2: The above method could be applied successfully, and the characteristics of Petri net can be used to analyze and optimize the project plan. In the process of task execution, if one activity is modified, other related activities will be automatically adjusted because of the correlation between them.

IV. A RESOURCE LEVELING OPTIMIZATION MODEL FOR MULTI-PROJECT NETWORK PLAN

Resources are the necessary conditions such as equipment, site, manpower, and funds required during project implementation. The core of multi-project management is how to achieve optimal allocation of resources. The above method realizes the work breakdown of the multi-project network plan and the arrangement of the activity schedule. After the project schedule is formulated, the resource planning of the project is needed to determine the resource requirements of the project activities. In a multi-project environment, with the increase of the project scale and the number of activities, the coordination and balance of resources is more complicated and difficult than a single project, and it has a greater impact on management efficiency and project costs. For a complex network plan that contains multiple projects, there is often parallel relationship between projects, and resources are often shared between project activities. Due to the limited amount of resources, resource requirements between activities are prone to conflict. Therefore, how to allocate activities to meet their respective resource requirements on the premise of meeting the duration of each project is the key to the implementation of the overall project.

Based on the above research of complex project network plan based on BOM, this paper discusses the resource leveling optimization problem of multi-project. For large-scale network plan, it is often difficult to achieve the ideal state of resource leveling. However, by adjusting the start time of non-critical activities in the project, resource requirements can fluctuate within the ideal range, so as to achieve higher resource utilization. There are many kinds of indicators for measuring resource leveling, such as variance σ, standard deviation, range R, and imbalance coefficient K. In this paper, variance is used as the optimization goal, that is, to minimize resource variance by adjusting the start time of each activity in the network plan. In order to facilitate the study of the problem, the following assumptions are made for the resource leveling optimization problem:

1) There are preceding and succeeding constraints on activities, and the constraints remains unchanged during the process of resource equilibrium;
2) Once the activity starts, no interruption is allowed until the end of the activity;
3) The resource consumption and supply of the activity keeps stable in the duration of the activity;

The mathematical model of resource leveling optimization for multi-project network plan can be expressed as follows:

$$\min \sigma^2 = \frac{1}{T}\sum_{\mathrm{t=1}}^{T}\left(R(t)-\bar{R}\right)^2 \tag{1}$$

$$R(t)=\sum_{\mathrm{i=1}}^{\mathrm{n}}\sum_{\mathrm{j=1}}^{\mathrm{m}} r_{ij}(t) \tag{2}$$

$$s_{ij} = t_{ij}^L - t_{ij}^E \tag{3}$$

$$\max\left\{t_{ik}^S + t_{ik}\right\} \leq t_{ij}^S \leq t_{ij}^L \tag{4}$$

$$t_{ij}^E \leq t_{ij}^S \leq t_{ij}^E + s_{ij} \tag{5}$$

$R(t)$ is the resource consumption of all activities in day t, $\bar{R}$ is the average daily resource consumption, $r_{ij}(\text{t})$ is the resource consumption of activity v_{ij} in project P_i on day t, t_{ij}^E represents the earliest start time of activity v_{ij}, t_{ij}^L represents the latest start time of activity v_{ij}. t_{ij}^S represents the actual start time of activity v_{ij}, t_{ij} represents the duration of activity v_{ij}, activity v_{ik} is the preceding activity of activity v_{ij}, s_{ij} is the relaxation time of activity v_{ij}, n is the total number of projects in the network plan, m is the total number of activities in project P_i.

In the above equations, (1) is the objective function, and the global optimization goal is to minimize the variance in the total resource consumption; (2) defines the resource consumption of the activity on day t; (3) defines the time window of the activity; (4) is the constraint on the activity start time; (5) indicates that an activity must begin after its preceding activities have been completed.

V. DESIGN AND IMPLEMENTATION OF ALGORITHM

For the solution to resource leveling problem, the commonly used methods include heuristic algorithm, particle swarm algorithm, genetic algorithm and other intelligent algorithms. Heuristic methods mostly depend on the construction of the problem and practical experience, and may bring new resource imbalance problem after each calculation, so it needs multiple repeated calculations to obtain the optimal solution. Particle swarm optimization is a stochastic optimization algorithm based on group iteration, which has high accuracy and fast convergence. However, due to the limitation of its inertia weight, it is easy to fall into the local optimal solution. Genetic algorithm has good implicit parallelism and good global search ability. It only uses fitness value as the search basis in the search process, which reduces the dependence on the mathematical model. There are not many restrictions on the problem to be solved. It can make the solution more efficient and practical by designing a genetic algorithm suitable for the problem. In this paper, an improved genetic algorithm is proposed to solve the resource leveling problem of the above multi-project network plan.

For the multi-project network planning resource balance optimization problem, this paper intends to use an improved genetic algorithm to solve, including the transformation of project resource balance problem, the selection of non critical activities, so as to reduce the complexity as well as to improve the efficiency of the algorithm. In addition, through the adjustment of algorithm crossover mode, the diversity of population can be maintained in the process of algorithm solving.

A. TRANSFORMATION OF RESOURCE EQUILIBRIUM PROBLEMS

According to the mathematical model of network plan resource leveling, it can be seen that the relaxation time of non-critical activities needs to be used, and the start time of non-critical activities needs to be adjusted according to the relaxation time to minimize the variance in the total resource consumption of all activities. If each activity is taken as a path, the arrangement of all activities constitutes the overall path of the entire project implementation. Therefore, if the relaxation time of an activity is taken as a variable, then different paths of the activity can be defined. For example, the relaxation time of a non-critical activity v_{ij} of the project P_i in a network plan is 3, that is s_{ij} = 3, then there are four optional paths to this activity, namely $L_{j,0}$, $L_{j,1}$, $L_{j,2}$, $L_{j,3}$, and the corresponding activity start time is t_{ij}^E, t_{ij}^E+1, t_{ij}^E+2, t_{ij}^E+3. Therefore, the resource leveling problem of network planning can be transformed into the optimization problem of multi-path selection. As shown in Fig.7, it is an optional path representation of non critical activity v_1, v_2, v_3 in a project network plan.

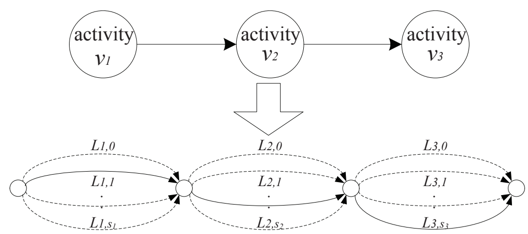


FIGURE 7. Transformation of the network plan resource leveling problem

B. DESIGN OF GENETIC ENCODING

For the coding design of the network plan coding, the paths of non-critical activities need to be converted into coding sequences. To this end, the optional path of each non-critical activity can be assigned a serial number according to the relaxation time, and the path selected by the non-critical activity can be regarded as a gene of the chromosome, then all the non-critical activities of the selected path together constitutes a encoding sequence, this encoding sequence can be used as a chromosome of the genetic code. The position of sequence number 1 is the path selected by the activity. As shown in Fig.8.

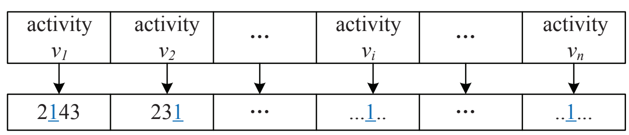


FIGURE 8. Design of genetic code

C. IMPROVE THE CROSSOVER OPERATION

For the above genetic encoding, the cross operation can't be carried out directly with the whole coding as a sequence. This paper adopts the method of internally crossing each active subsequence, and then concatenates to form a new encoding sequence. In this paper, block crossing method is

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3078840, IEEE Access

used, as shown in Fig.9, P_1 and P_2 are two parent individuals, $P_1 = 1234$, $P_2 = 2143$, Select a cross area among the parent individuals, then place the cross area of P_1 in front of P_2, place the cross area of P_2 in front of P_1, and then delete the same number as in the crossing area. Finally, we get two individuals: $C_1 = 1423$, $C_2 = 2314$. Compared with other crossover methods, the block crossing method can still produce new offspring when the parents are the same, thus ensuring the diversity of the population.

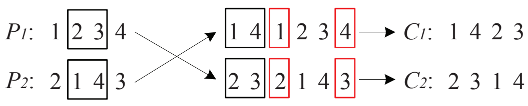


FIGURE 9. Block crossing method

Remark 3: This paper uses the relaxation time of non-critical activities to convert the resource balancing problem into a multi-path selection problem, and at the same time, designs a cross operation to improve the algorithm's global optimization ability.

VI. A CASE STUDY

In order to solve the resource leveling problem of multi-project network planning and verify the feasibility of the model and algorithm proposed in this paper. This network plan according to Fig.10 is taken as an example of optimization. The network plan contains two projects with a total of 16 activities. The parameters are set as: population number 8, iterations 80, crossover probability 0.4, and mutation probability 0.2. The calculated results are shown in Fig.11 $\sim$ Fig.13. Fig.11 is an iterative curve of the resource variance in the optimization process, Fig.12 is a comparison of the network plan arrangement before and after optimization, and Fig.13 is a comparison of the resource leveling before and after optimization.

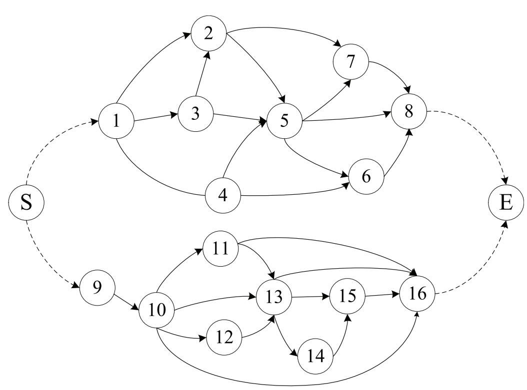


FIGURE 10. Example of network plan resource leveling

Fig.14. and Fig.15. show the change of resource variance when the number of projects and activities changes. Fig.14. show the change of resource variance when the shows the change trend of the maximum and minimum resource variance when the number of projects remains unchanged but

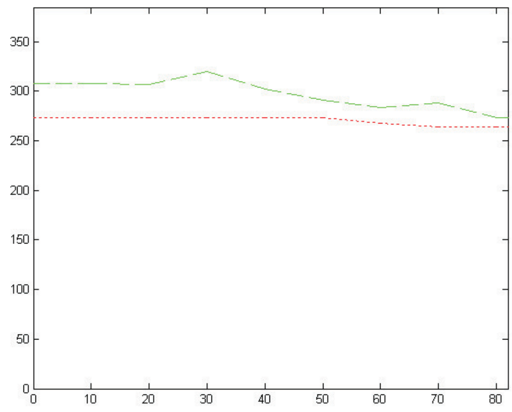


FIGURE 11. Iterative curve of resource variance

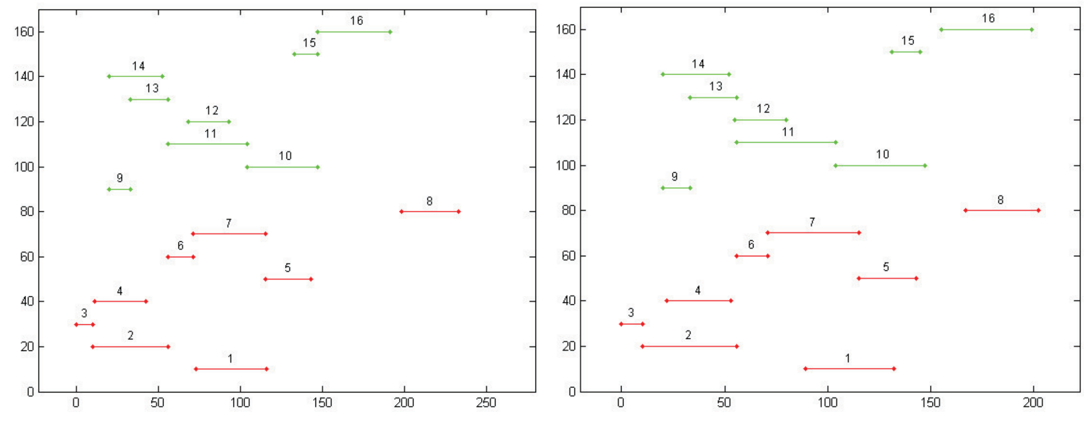
the number of activities increases. Fig.15. shows the change trend of the maximum and minimum resource variance when the number of projects increases but the total number of activities remain unchanged. It can be seen from the figure that resource variance changes with the number of activities and items However, the growth rate of the maximum and the minimum variance keeps stable.

Fig.16 and Fig.17 show comparisons before and after optimization of the network plan and resource leveling for 120 activities in 5 projects.

Through the above examples, it can be seen from the optimization results that the maximum daily resource demand before and after optimization is 262 units and 237 units, and obvious equilibrium effect has been achieved after optimization. In addition, the fluctuations in the resource demand after optimization tends be balanced, which will also play a role in saving resources and reducing project costs. Compared to single project, the multi-project resource leveling problem is more complicated, and the resource requirements of each project activity conflict with each other. The improved genetic algorithm proposed to this paper can obtain a better project planning scheme, which makes the multi-project resource allocation better.

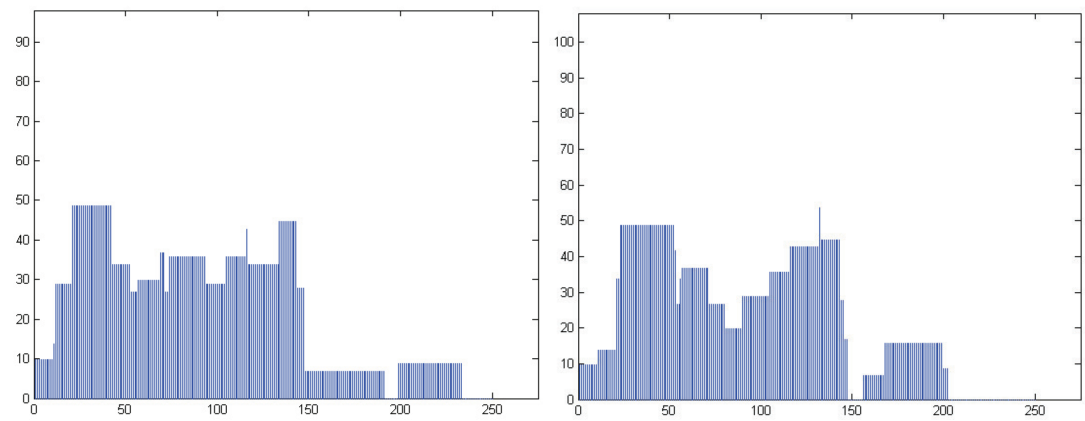
For further analysis and comparison, the improved genetic algorithm in this paper is compared with particle swarm optimization algorithm and ant colony algorithm. In the design of particle swarm optimization algorithm, we set the fluctuation range of particles according to the key activities, and set the dimension of particle swarm according to the number of key activities, and these settings can be automatically adjusted according to the different projects and activities of each example. In the design of ant colony algorithm, we set different paths according to the key activities, and the selection probability of the path is determined by pheromone and random factors. The project, activity, quantity and time cycle of all examples are automatically generated by our program. The parameters of genetic algorithm are set as follows: population 10, crossover probability 0.4, mutation probability 0.2, normalized elimination acceleration index

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3078840, IEEE Access



(a) (b)

FIGURE 12. Comparison of network plans before and after optimization



(a) (b)

FIGURE 13. Comparison of resource leveling before and after optimization

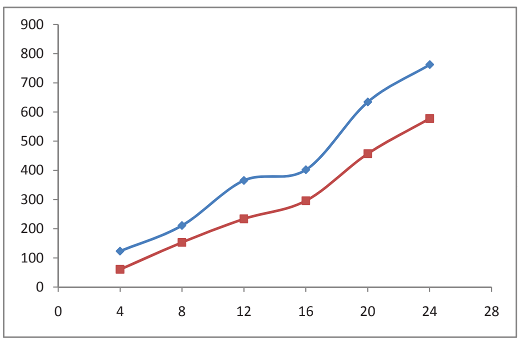


FIGURE 14. Variance change of resources when the number of projects keeps unchanged

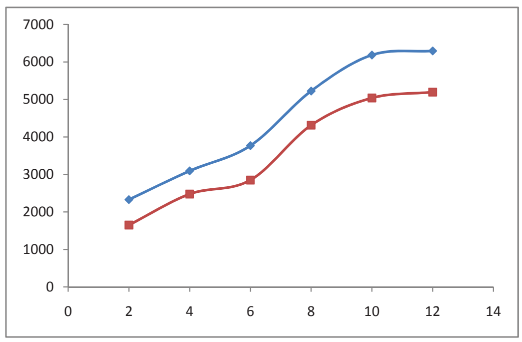
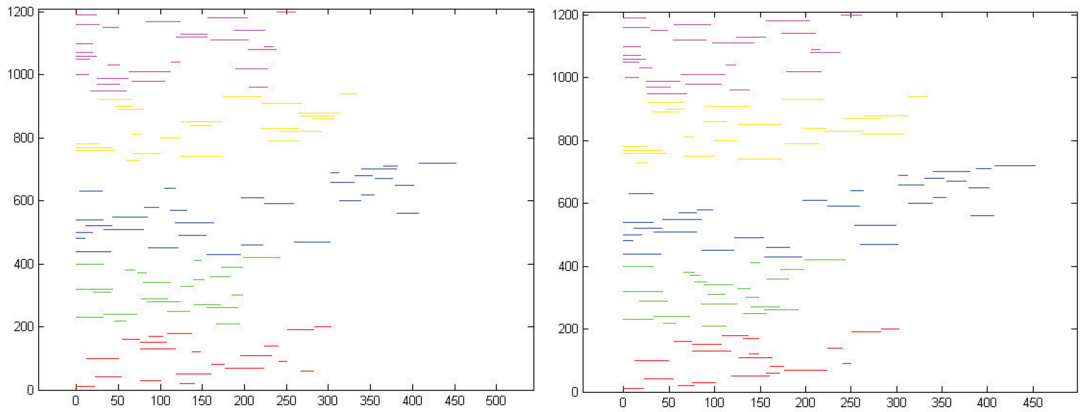


FIGURE 15. Variance change of resources when the number of activities keeps unchanged

1.5; the parameters of genetic algorithm are set as follows: particle swarm size 40, individual experience learning factor 2, social experience learning factor 2, inertia factor 0.6, maximum flying speed 0.8; the parameters of ant colony algorithm are set as follows: number of ant colony 15, heuristic factor 4, The expected heuristic factor is 3, the information intensity is 8, and the pheromone evaporation factor is 0.1. The iterations of the three algorithms are all 100. In this paper, matlab r2012b is used for experimental analysis. The experimental data comparison is shown in Fig.18.

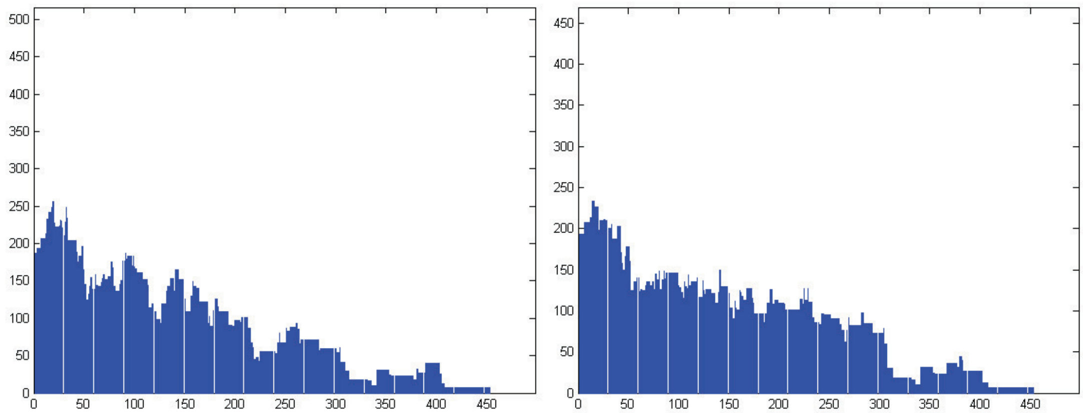
Fig.18 (a) shows the resource balance optimization comparison of three algorithms for the network plans of three

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3078840, IEEE Access



(a) (b)

FIGURE 16. Comparison of network plans before and after optimization



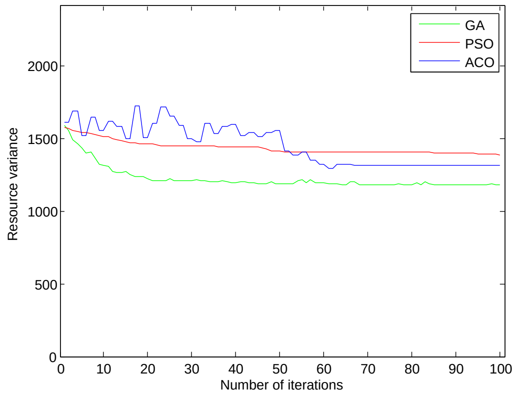
(a) (b)

FIGURE 17. Comparison of resource leveling before and after optimization

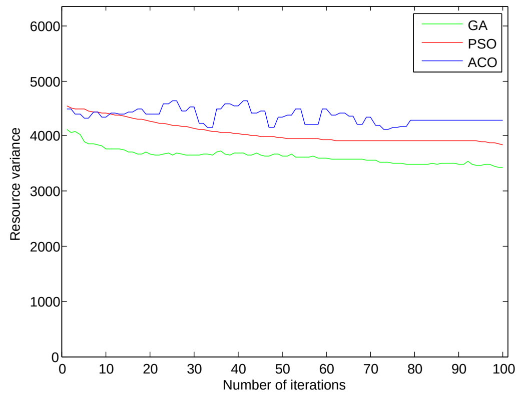
projects with 70 activities, and Fig.18 (b) shows the resource balance optimization comparison of the network plans of five projects with 120 activities. From the results in the figure, it can be seen that after 100 iterations, GA, PSO and ACO can get the average results. The resource variances are 1176, 1387 and 1312 respectively. For the optimization of five projects, after 100 iterations, the average resource variances obtained by the three algorithms are 3427, 3845 and 4288 respectively. In the two examples, the improved genetic algorithm used in this paper obtains better results. Now the experimental curves of the three algorithms are analyzed and compared:

1) Particle swarm optimization target value curve: in the three project examples, in the previous 20 iterations, the slope of the curve shows that the convergence speed of the algorithm is faster, and then the curve is relatively gentle. It can be seen that the algorithm has carried out many redundant iterations during this period, and the efficiency of the solution is reduced. In the five project examples, with the increase of the number of activities, the convergence speed of the algorithm is slower, the curve becomes more gentle after 40 iterations, and the efficiency of the solution is lower.
2) Ant colony algorithm target value curve: compared with other two algorithms, the curve fluctuation is relatively large. In the three project examples, the fluctuation degree of curve starts to decrease from the 35th time, and converges rapidly at 50-60 times. Among the five projects, the fluctuation degree of curve starts to decrease from the 50th time, and converges rapidly at 60-80 times. It can be seen that the fluctuation degree of curve is not reduced with the increase of activity number, and the fluctuation interval is extended. Ant colony algorithm itself is prone to fall into local optimal problem. Improper setting of parameter value may cause this problem. However, the parameter of this algorithm is still fluctuated after adjustment. Therefore, the change of parameters does not improve the solution effect of the algorithm.
3) The objective value curve of the improved genetic

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3078840, IEEE Access



(a)



(b)

FIGURE 18. Comparison of target value curves of three algorithms

TABLE 1. Comparison of resource balance optimization of different project network plans

Number of projects	Number of activities	value before optimization	GA optimal value	GA average value	PSO optimal value	PSO average value	ACO optimal value	ACO average value
1	20	3572	1465	1628	1565	2288	2136	2136
3	70	1895	1176	1176	1175	1387	1312	1312
4	90	1544	852	854	843	979	1055	1055
5	120	5087	3424	3427	3611	3845	4288	4288
7	180	8383	5471	5476	5793	6265	7516	7516
10	240	17775	12191	12229	13318	13993	15394	15394

algorithm: in the two examples, the curve converges rapidly in the first 20 iterations, and the solution efficiency is very high. After that, the convergence speed of the curve tends to be stable and the efficiency of the solution is relatively low. Compared with particle swarm optimization and ant colony algorithm, the convergence speed and efficiency of the curve are faster and more efficient in the whole iteration period. Although the fluctuation of curve is slightly larger than that of PSO, the variance value is better than the other two algorithms in the whole iteration cycle.

Tab.1 shows the data comparison of the resource variance optimization of the network plans with six different projects and activities by the three methods.

Comparing the improved genetic algorithm with particle swarm optimization and ant colony algorithm, we can see that the algorithm proposed in this paper is better than particle swarm optimization and ant colony algorithm in solving efficiency and optimal value. Compared with these two algorithms, the algorithm in this paper is not easy to fall into local optimum, and the solving effect is better. Compared to single project, the multi-project resource leveling problem is more complicated, and the resource requirements of each project activity conflict with each other. The improved genetic algorithm proposed to this paper can obtain a better project planning scheme, which makes the multi-project resource allocation better.

VII. CONCLUSION

Due to the complexity of the production and assembly process of large complex equipment, and the simultaneous development of multiple projects, there are often conflicts between projects and their activities, and the project planning becomes extremely complex. To solve this problem, we studied the BOM and production characteristics of large and complex projects, and proposed a network plan decomposition method. This method can decompose and simplify the BOM of large and complex projects. This method can decompose and simplify the BOM of large and complex projects. The project network plan can be formed by mapping the Petri net cell rules, and then the start and end time of each project activity can be obtained according to the Petri net mapping algorithm, and finally a complete project network plan with time planning can be created. In addition, aiming at the resource leveling problem of the decomposed project network plan, this paper built a multi-project resource leveling model, proposed a genetic algorithm method, and improved the coding design and crossover operation. On this basis, by adjusting the optimal start time of non-critical activities, the resource can be balanced when multiple projects are running in parallel, and the algorithm was verified by an example. Finally, through case study, the algorithm is compared with particle swarm optimization algorithm and ant colony algorithm. The results show the algorithm proposed has better efficiency, stability and optimal value for multi project resource balance optimization. Through the research in this paper, an effective method was proposed to the plan decomposition and resource leveling optimization of large and complex projects. Subsequently, on the basis of the above research, the resource optimization of large and complex projects can be further studied from the perspective of multi-mode resource constraints and equilibrium.

REFERENCES

[1] Z. X. Su, J. X. Qi and Z. N. Kan, "Simplifying activity networks under generalized precedence relations to extended CPM networks," *Int. T. Oper. Res*., vol. 23, Apr. 2015.

[2] K. Nakade, T. Narumi, "Indices to critical activities in stochastic PERT Networks," *IEEE Int. Conf. Ind. Eng*., pp. 666-670, Dec. 2015.

[3] A. Bozhenyuk, M. Knyazeva and I. Rozenberg, "A graph multi-mode approach to modeling and solving scheduling problem with limited resources," *2017 IEEE Int. Conf. Fuzzy Syst*., pp. 1-6, Jul. 2017.

[4] N. Zhang *et al.*, "Module partition of complex mechanical products based on weighted complex networks," *J. Intell. Manuf*., vol. 30, Apr. 2019.

[5] Xing-Mei Li *et al.*, "The Project Network with Learning Effect and Time-Switch Constraints,"*J. Ind. Eng*., vol. 29, no. 2, pp. 63-39, Feb. 2015.

[6] Mourad *et al.*, "Critical links detection in stochastic networks: application to the transport networks,'‘ *Int. J. Int. Comput. Cybern*., vol. 12, no. 1, pp. 42-69, Feb. 2019.

[7] V. P. Joost *et al.*, "Parametric Critical Path Analysis for Event Networks with Minimal and Maximal Time Lags," *IEEE T. Comput. Aid. D*., vol. 37, no. 11, pp. 2697-2708, Jul. 2018.

[8] Y. Saeed and Amir Azaron, "Resource allocation in multi-class dynamic PERT networks with finite capacity," *Eur. J. Oper. Res*., vol. 247, no. 3, pp. 879-894, Jun. 2015.

[9] Mourad *et al.*, "Indices to critical activities in stochastic PERT Networks," *IEEE Int. Conf. Ind. Eng*., vol. 22, pp. 37-52, Sep. 2016.

[10] S. Creemers, "Minimizing the expected makespan of a project with stochastic activity durations under resource constraints," *J. Sched*., vol. 18, no. 3, pp. 263-273, Jun. 2015.

[11] S. Adhau, M. Mittal and A. Mittal, "A multi-agent system for decentralized multi-project scheduling with resource transfers," *Int. J. Prod. Econ*., vol. 146, no. 2, pp. 646-661, Dec. 2013.

[12] T. Wauters *et al.*, "A learning-based optimization approach to multi-project scheduling," *J. Sched*., vol. 18, no. 1, pp. 61-74, Feb. 2015.

[13] Z. Q. Lu and C. Yang, "Modeling of Resource Constrained Multi-Project Scheduling Problem Based on Project Splitting," *J. Shanghai Jiaotong Univ*., vol. 51, no. 2, pp. 193-201, Feb. 2017.

[14] C. Meloni and M. Pranzo, "Expected shortfall for the makespan in activity networks under imperfect information," *Flex. Serv. Manuf. J*., vol. 32, no. 1-2, pp. 1-25, Sept. 2020.

[15] H. Li and X. Dong, "Multi-mode resource leveling in projects with mode-dependent generalized precedence relations," *Expert Syst. Appl*., vol. 97, pp. 193-204, Dec. 2017.

[16] L. Wang *et al.*, "Heuristic algorithm for solving multi-project collaborative scheduling problem with activity splitting," *Control Decis*., vol. 32, no. 6, pp. 1013-1018, Jun. 2017.

[17] M. Rostami and D. Moradinezhad, "Improved and competitive algorithms for large scale multiple resource-constrained project-scheduling problems," *KSCE J. Civ. Eng*., vol. 18, no. 5, pp. 1261-1269, Jun. 2014.

[18] JL. Ponz-Tienda, A. Salcedo-Bernal and E. Pellicer, "A Parallel Branch and Bound Algorithm for the Resource Leveling Problem with Minimal Lags," *Comput.-Aided Civil Infrastruct. Eng*., vol. 32, no. 6, Aug. 2016.

[19] C. José and M. Vanhoucke. "An exact composite lower bound strategy for the resource-constrained project scheduling problem," *Comput. Oper. Res*., vol. 93, Feb. 2018.

[20] M. J. Geiger, "A multi-threaded local search algorithm and computer implementation for the multi-mode, resource-constrained multi-project scheduling problem," *Eur. J. Oper. Res*., vol. 256, no. 3, pp. 729-741, Mar. 2017.

[21] N. Cui and Y. Liang, "Robust project scheduling based on the integrated optimization between resource flow network and time buffers," *Syst. Eng. Pract*., vol. 38, no. 1, pp. 102-112, Jan. 2018.

[22] Azami, K. Demirli and N. Bhuiyan, "Scheduling in aerospace composite manufacturing systems: a two-stage hybrid flow shop problem," *Int. J. Adv. Manuf. Technol*., vol. 95, no. 4, pp. 1-16, Apr. 2018.

[23] Q. Wang, C. Liu and L. Zheng, "A column-generation-based algorithm for a resource-constrained project scheduling problem with a fractional shared resource," *Eng. Optimiz*., vol. 52, no. 6, pp. 1-19, May. 2019.

[24] Okada *et al.*, "A genetic algorithm with local search using activity list characteristics for solving resource-constrained project scheduling problem with multiple modes," *IEEJ Trans. Electr. Electron. Eng*., vol. 11, no. 2, pp. S34-S43, Dec. 2016.

[25] J. Li *et al.*, "A multi-objective memetic algorithm for integrated process planning and scheduling," *Int. J. Adv. Manuf. Technol*., vol. 85, no. 5-8, pp. 1513-1528, Jul. 2016.

[26] Mohammad *et al.*, "Multi-project Time-cost Optimization in Critical Chain with Resource Constraints," *KSCE J. Civ. Eng*., vol. 22, no. 10, pp. 3738-3752, Jul. 2018.

[27] X. Wang, F. Yalaoui and F. Dugardin, "Genetic algorithms hybridized with the self controlling dominance to solve a multi-objective resource constraint project scheduling problem," *IEEE Int. Conf. Serv. Oper*., Dec. 2017.

[28] J. Yu, Z. Xu and H. B. Li, "Modeling and solving the resource-constrained project scheduling problem with activities overlapping," *Syst. Eng. Pract*., vol. 35, no. 5, pp. 1236-1245, Jan. 2015.

[29] Damci, D. Arditi and G. Polat, "Impacts of different objective functions on resource leveling in Line-of-Balance scheduling," *KSCE J. Civ. Eng*., vol. 20, no. 1, pp. 58-67, Mar. 2015.

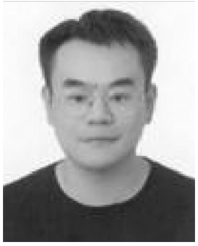
[30] Z. H. Chu, Z. Xu and J. Yu, "Multi-mode resource-constrained project scheduling problem with activities overlapping," *Comput. Integr. Manuf. Syst*., vol. 23, no. 3, pp. 557-566, Mar. 2017.

[31] M. Yazdani, M. Zandieh and R. Tavakkoli-Moghaddam, "Evolutionary algorithms for multi-objective dual-resource constrained flexible job-shop scheduling problem," *OPSEARCH*, vol. 56, no. 3, pp. 983-1006, Jul. 2019.

FIRST A. AUTHOR (F'61) received a doctorate in mechanical manufacturing and automation from Beihang University in 1999. She is now a professor of School of mechanical engineering and automation of Beihang University, a visiting professor of central Polytechnic University of Nantes in 2010, and a visiting professor of National Institute of higher engineering and technology of France in 2012. The research fields include product development engineering, product life cycle modeling and management, digital manufacturing and intelligent manufacturing. Focusing on model-based product definition, digital process design, tolerance analysis and simulation, manufacturing knowledge modeling and management, and information integration, he has successively presided over and undertaken the National Natural Science Foundation of China, National Science and technology research plan, and national 863 plan , Ministry pre research, enterprise engineering projects and international exchange and cooperation projects. He has been invited to many universities and research institutions in the United States and France to carry out cooperative research.

SECOND B. AUTHOR (M'82) received a master's degree in mechanical engineering from Beihang University in 2006. Now he is a doctoral student majoring in mechanical engineering from Beihang University. His research fields include project planning management, production scheduling and intelligent scheduling algorithm.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2021.3078840, IEEE Access



THIRD C. AUTHOR (M'91) received a master's degree in mechanical engineering from Beihang University in 2015 and Ecole national sup é rieure d'arts et m é tiers (ensam) in 2018 He is an assistant professor of School of mechanical engineering and automation, Beihang University. His research fields include additive manufacturing, product geometry specification, knowledge engineering, digital and intelligent manufacturing.