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Review of Cost-Oriented Maintenance Resource Allocation and Task Scheduling Problems

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Abstract: *The maintenance of complex equipment typically involves considerations such as cost control, resource allocation, workflow constraints, task mode selection, and maintenance deadlines, making it a complex resource-constrained project scheduling problem. This article first elaborates on the background of cost-oriented maintenance resource allocation and task scheduling. Next, it reviews and analyzes the current research status of related areas, including resource-constrained project scheduling, multi-project resource leveling, and resource allocation cost problems. Finally, potential future research directions are discussed.*

Keywords: *Complex Equipment Maintenance; Resource Allocation; Cost Optimization; Project Scheduling*

1. Introduction

Cost is the primary concern for complex equipment maintenance contractors. However, since maintenance contracts typically specify both the total project budget and completion deadlines, optimizing resource allocation to minimize total costs becomes critical for contractors. Given that most maintenance projects are executed concurrently in multi-project environments [1], and resources can be transferred between projects, developing an integrated resource allocation strategy and corresponding multi-project execution plan to minimize overall maintenance costs holds significant practical value for contractors.

A maintenance project generally consists of multiple strictly time-constrained tasks, each requiring a defined duration and specific resources, with associated costs for every unit of allocated resources. To minimize resource allocation costs while meeting project deadlines, proper resource distribution and corresponding execution plans must be developed. In academic research, this challenge is defined as the Resource Availability Cost Problem (RACP), a classic NP-hard problem. When multiple projects run concurrently with inter-project resource transfers, the RACP model becomes inadequate, necessitating a joint resource allocation and scheduling approach across all projects.

At present, research on the cost of resource allocation for multiple projects mainly focuses on three aspects: the first aspect is the multi project scheduling problem under resource constraints, which focuses on how to jointly schedule multiple projects that are executed in parallel with a fixed number of resources to minimize the weighted sum of project durations for all projects; The second aspect is the Resource Leveling Problem (RLP), which focuses on scheduling project tasks to achieve a balanced total resource demand during the project completion process when resources are limited and project schedules are determined; The third aspect is the classic problem of resource allocation cost, which focuses on how to allocate resources while scheduling project tasks to minimize project costs for a single project with a fixed schedule.

2. Multi project scheduling problem under resource constraints

Parallel execution of multiple projects is a common situation in practice [1], and a fixed total amount of resources will inevitably lead to resource competition between projects. It is important for practical project management to develop a reasonable plan for the transfer of resources between projects and a reasonable work schedule based on project needs. To this end, Shou Yuying [2] established a mathematical model for multi project scheduling problems under resource constraints, and designed an

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iterative algorithm for multi project scheduling based on a single project scheduling algorithm. The algorithm optimizes project duration from a global perspective while ensuring temporal constraints and resource limitations between project tasks. Afterwards, researchers proposed many derivative models based on the resource constrained multi project scheduling model according to the actual problems encountered. Wang Jianqi [3] constructed a multi-objective optimization model for resource constrained multi project scheduling problems, using a constraint layer by layer decomposition strategy to process the temporal and resource constraints of the project in two stages, in order to solve the multi-objective optimization model. Hu Wenbin [4] studied a modeling method based on extended Petri nets for projects with variable and non variable project schedules, modeling the two scenarios of schedule determination and variable schedule separately. Xiang Wenwen [5] focuses on uncertain conditions and studies the problem of project portfolio selection and scheduling under limited resources. She proposes to link the two levels of project portfolio and project scheduling, and then carry out work separately from the levels of project portfolio selection and task scheduling to effectively control project risks. Fang [6] proposed a multi project optimization scheduling model that comprehensively considers multi project delay costs, renewable resource idle costs, and renewable resource transition costs. Then, a hybrid ant colony algorithm was designed to solve the model, effectively reducing project costs. Although these derivative models have expanded the applicability of multi project scheduling problem models under resource constraints, they have not changed the NP hard nature of the problem, nor have they reduced the complexity of model solving.

In response to the problems of complex and inefficient model solving, there are still many researchers focusing on the efficiency of model solving algorithms. Gon ç alves [7] solved the problem using genetic algorithm based on random key expression, and designed a heuristic algorithm to improve the quality of the solution, achieving very good results and becoming one of the most cited papers in this field, laying the foundation for further research by future generations. Guo [8] proposed an improved quantum evolutionary algorithm and applied it to solve multi project scheduling problems, resulting in solutions with better quality and efficiency than classical genetic algorithms. Toffolo [9] used integer programming to solve the multi-modal resource constrained multi project scheduling problem, which is an accurate solving algorithm. Although the solving efficiency is high, it is only suitable for situations with a small number of tasks. Yan [10] proposed an improved evolutionary computation algorithm and designed a parallel mutation strategy to effectively improve the quality of solutions. Finally, the algorithm was compared with other solving algorithms to demonstrate its efficiency. Wauters [11] reviewed the research results of multi project scheduling problems, analyzed some of the challenges faced in the research of multi project scheduling problems, and summarized the commonalities of existing research. Suresh [12] considers the time cost of resource transfer between projects and establishes a resource constrained multi project scheduling model that takes into account the cost of resource transfer. A new genetic algorithm is proposed to solve the model, and experimental results are provided for future reference.

The multi project scheduling problem under resource constraints has always been a research hotspot in the field of project scheduling [13-15], but the existing research mainly focuses on how to improve resource utilization efficiency and shorten project duration under limited resources, with less attention paid to resource allocation costs.

3. The problem of resource balance in multiple projects

The multi project resource balancing problem [16] is a practical significance for reducing project management costs and lowering project risks by jointly scheduling multiple projects to ensure that each project is completed on schedule while maintaining stable resource requirements. Hegazy [17] believes that there is an inseparable relationship between the allocation of project resources and the balance of resources. Therefore, he established a joint optimization model for project resource allocation and balance, and then designed a solving algorithm based on genetic algorithm to allocate limited resources to multiple projects that are executed in parallel, and schedule project tasks to stabilize resource demand. This provides valuable reference for future research on resource balance problems in multiple projects. Subsequently, researchers have continuously expanded the problem of multi project resource balance, established numerous models closely related to actual project management, and designed various efficient model solving algorithms.

Woodworth [18] designed a heuristic algorithm to solve the problem of resource balancing in multiple projects, which reduces the total demand for resources while balancing resource demands. Taghaddos [19] uses simulation methods to solve the problem of resource balance in multiple projects, and designs corresponding solving algorithms in the simulation model to achieve better solutions to the problem.

Based on the research of resource balance problem, Alsayegh [20] proposed to establish a resource balance model by minimizing the cost of resource allocation, and solved the model using particle swarm optimization algorithm and simulated annealing algorithm. The efficiency of the two solving algorithms was compared. His research method not only solves the problem of project resource balance, but also provides valuable reference for the problem of resource allocation cost. Wang Kai [21] applied the theory of multi project resource balance in the aviation field and transformed the multi project resource balance problem into a single project resource balance problem. Then, he used artificial immune algorithm to solve the model, making the resource demands of multiple projects tend to be stable. Wang Qiuquan [22] aimed at the disadvantage of easily falling into local optimal traps when using particle swarm optimization algorithm to solve resource balance problems, and fused particle swarm optimization algorithm and simulated annealing algorithm to greatly improve the efficiency of the solution. Yu Haifu [23] applied particle swarm optimization algorithm to the optimization problem of resource balance in aviation projects at a deeper level, solving the problems of low resource utilization and concentrated demand caused by excessive tasks in aviation projects. Zhou Xiaoyang [24] established a dual layer equilibrium model for resource allocation in multiple projects under uncertain conditions, aiming to expand the research on resource equilibrium to uncertain conditions and increase the adaptability of the model.

The existing research on resource balance in multiple projects [25] mainly focuses on improving resource utilization efficiency and promoting stable resource demand, with some studies dedicated to optimizing both resource demand and resource cost simultaneously. The problems addressed by these research institutes have many similarities with the issue of resource allocation costs in multiple projects, and have important reference value for solving the problem of resource balance in multiple projects.

4. Research on the Cost of Resource Allocation

The problem of resource allocation cost was first proposed by M ö hring [26], who first established a mathematical model for the problem and proved that it is a more complex NP hard problem than project scheduling under resource constraints. Then, he used graph theory based methods to solve the model. Demeulemeester [27] used the branch and bound method to solve the resource allocation cost problem and designed a test case library. Drexel [28] combines the characteristics of this problem and designs algorithms to estimate the lower limits of various resource allocation. It also points out that if a compromise can be made between project duration and project cost, it has important practical significance for actual project management. Yamashita [29] used a decentralized search algorithm to solve the resource allocation cost problem and tested the algorithm using examples from the project scheduling problem library (PSPLIB) [30]. Later, a robust optimization model was established to address the uncertainty of job time [31]. Rodrigues [32] proposed an exact solution method based on the branch and bound method, but experimental results showed that this solution method is only suitable for situations with a small number of tasks. When there are a large number of tasks, model solving becomes very difficult. Ranjbar [33] combines genetic algorithm and path reconnection algorithm, and then applies them to solve the resource allocation cost problem and designs a new heuristic algorithm that can improve the convergence speed of the entire algorithm and enhance the quality of feasible solutions. Peteghem [34] attempted to solve the problem using artificial immune algorithm, proposed a new fitness function, and designed a prevention mechanism to avoid premature convergence of the algorithm. Afshar [35] uses an adaptive greedy search algorithm to solve the model and suggests that research on resource allocation costs can be expanded, such as considering more complex temporal constraints between jobs and multi execution mode problems of jobs. The project applicant [36] uses an improved particle swarm optimization algorithm that integrates path reconnection algorithm to solve the problem, and designs a heuristic algorithm based on direct expression to improve the efficiency of model solving. The above research results on RACP problems focus on the efficiency of solving model algorithms, with less emphasis on the resource allocation cost model and no extension of the model.

Yamashita [37] extended the problem of resource allocation cost from a single execution mode to multiple execution modes, and constructed a multi mode resource availability cost problem (MMRACP) model for job multi execution modes. Then, intelligent optimization algorithms were used to solve the model, and the relationship between total project cost and duration was analyzed. Due to Yamashita's [37] model only considering renewable resources and not taking into account non renewable resources, Qi Jianjun [38] established a resource allocation cost problem model for job multi execution modes that simultaneously cover both renewable and non renewable resources, and solved the model based on an improved particle swarm optimization algorithm. To further improve the solving efficiency of the model, Qi Jianjun [39] proposed a pre task list encoding expression method, and then applied this expression method to solve the resource allocation cost problem in multi execution mode of tasks. Corresponding heuristic algorithms were designed to greatly improve the solving efficiency of the model. Nadjafi [40] used simulated degradation algorithm to solve the model and pointed out that the problem of multi execution mode of homework is more practical than the problem of single execution mode of homework.

The existing RACP problems mostly focus on optimizing the resource allocation cost of individual projects, with the main research emphasis on the efficiency of model solving algorithms [41-43]. At present, no one has conducted research on the issue of resource allocation costs for multiple projects, let alone established corresponding models.

5. Development dynamic analysis

Through summarizing and analyzing the current research status at home and abroad, the development trend of research on project resource allocation costs is mainly reflected in the following aspects:

(1) The problem of multi project resource allocation cost with negligible resource transfer cost. In some cases, the cost of qualification allocation is too expensive, and the cost of resource transfer can be ignored. This is the simplest situation in the multi project resource allocation cost problem, and it is also the basis for studying other multi project resource allocation cost problems. This problem is no longer a simple combination of resource allocation costs for multiple individual projects, but requires viewing all projects as a whole and analyzing them from the top level, then establishing a model and designing a model solving algorithm. The complexity of this model will be higher than that of the single project resource allocation cost problem model, and the difficulty of solving it will also be greater.

(2) The problem of multi project resource allocation cost considering resource transfer cost. The cost of resource transfer generated during the process of resource transfer between projects is difficult to ignore in some cases, and in this case, the cost of resource transfer must be considered in the process of configuring project resources and executing project execution plans. At present, research on resource constrained multi project scheduling problems has given more consideration to resource transfer costs, while research on resource allocation costs has not yet taken into account the impact of resource transfer costs on resource allocation schemes and project execution plans. Therefore, the issue of multi project resource allocation costs considering resource transfer costs will inevitably attract more and more researchers' attention and become a research hotspot in the field of project scheduling in the future.

(3) The problem of resource allocation cost for multiple projects with flexible construction periods. Delayed project delivery may increase additional costs while reducing resource allocation costs, while early project delivery may increase resource allocation costs while obtaining additional benefits. In this case, a reasonable balance needs to be made between the additional costs (or benefits) and resource allocation costs to ensure maximum overall project benefits. This type of issue is referred to as the resource allocation cost problem of flexible project duration in this project. Researchers have conducted studies on this, but these studies have only focused on individual projects and have not studied the situation of multiple projects being implemented in parallel. The parallel implementation of multiple projects will increase the complexity of the problem, bringing huge challenges to the establishment of models and the design of solving algorithms. However, due to the practical existence of the problem, it will inevitably attract widespread attention from researchers.

6. Conclusion

This article provides a systematic review of research progress and future trends in maintenance resource allocation and task scheduling with a focus on cost optimization. By analyzing resource-constrained multi-project scheduling, multi-project resource leveling, and resource allocation cost problems, it is evident that while significant achievements have been made by scholars worldwide, many challenges and opportunities for further exploration remain.

Current research primarily concentrates on single-project or resource-constrained scheduling optimization, with insufficient attention given to practical factors such as resource transfer costs and flexible deadlines in multi-project parallel execution. Particularly in multi-project resource allocation cost problems, the impact of resource transfer costs and the trade-off between project duration and costs have not been thoroughly investigated. Future research should focus on three key directions: (1) establishing multi-project resource allocation cost models where transfer costs are negligible, laying the foundation for complex scenarios; (2) exploring the influence of resource transfer costs on scheduling schemes and developing efficient solution algorithms; and (3) investigating flexible deadline multi-project resource allocation to balance project duration and costs, thereby maximizing overall benefits.

Furthermore, with advancements in intelligent optimization algorithms and computational technologies, integrating emerging techniques such as machine learning and big data analytics is expected to enhance the efficiency and applicability of model solutions. This review serves as a theoretical reference for future research and offers valuable insights for cost control and resource optimization in practical maintenance projects. Moving forward, studies should continue to align with real-world demands, driving the field toward greater efficiency and intelligence.

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