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A SURVEY OF THE PROBLEM AND TECHNIQUES IN RESOURCE ALLOCATION FOR MULTI-PROJECT SOFTWARE PROJECTS

Managing multiple software projects concurrently presents challenges in resource allocation. This study explores these issues and potential solutions. We conducted research to identify and categorise the most pressing problems in this domain and evaluate the effectiveness of various techniques proposed to mitigate these challenges. The key challenges identified are resource underutilisation, inefficiency, and conflict. Projects often suffer from long durations, uncertainties, and cost overruns. Traditional project management methods, such as the Critical Path Method and Program Evaluation and Review Technique, assume unlimited resources and are designed for single-project environments, rendering them inadequate for multi-project scenarios. Consequently, more recent research has explored advanced approaches to develop more effective scheduling solutions, including heuristic algorithms, genetic algorithms, and hybrid methods. Still, they lack performance guarantees and may not consistently achieve optimal results. The study examines how researchers tackle these issues. Techniques include using upper and lower bounds for concurrent activities, project buffers, and optimising project makespan for better resource utilisation. Additionally, allocating the right people to projects and coordinated planning for resource-constrained scenarios are explored. The research indicates that multi-stage hybrid approaches utilising machine learning techniques yield the most promising results. Therefore, future research should focus on applying ML techniques to select the optimal algorithm and incorporate historical data, representing a promising direction for advancing this field. This analysis provides insights for researchers seeking to develop improved approaches to resource allocation in multi-project software development.

Keywords: multi-project scheduling, portfolio project management, software engineering.

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ОГЛЯД ПРОБЛЕМ ТА МЕТОДІВ РОЗПОДІЛУ РЕСУРСІВ ДЛЯ БАГАТОПРОЄКТНИХ СЕРЕДОВИЩ ПРОГРАМНИХ ПРОЄКТІВ

Задача мультипроєктного планування в умовах обмеженості ресурсів є складною для вирішення через велику кількість обмежень, які необхідно враховувати, а також вимоги за часом і бюджетом, які часто суперечать одна одній. У цьому дослідженні розглядаються проблеми, пов'язані з програмними проєктами в мультипроєктному середовищі, та методи, які використовуються для їх вирішення. Шляхом системного аналізу опублікованих робіт за темою визначені часто використовувані методи і ключові проблеми в цій області. Дослідження показує, що багатоетапні гібридні підходи з використанням методів машинного навчання показують найбільш перспективні результати. Тому дослідження щодо використання методів машинного навчання не тільки для вибору найкращого алгоритму, але й для врахування історичних даних є перспективним напрямком для подальших досліджень.

Ключові слова: мультипроєктне планування, управління портфелем проєктів, програмна інженерія.

Statement of the problem

In the era of rapid technological advancement, the complexity of managing multiple software projects simultaneously has become a ubiquitous challenge across various industries. As organisations strive to keep pace with the fast-paced digital transformation, this multi-project environment has evolved into a complex web of interdependencies and competing priorities. While it offers numerous benefits, such as resource optimisation and diversified risk [1], it also introduces many challenges that can significantly hinder effective project planning and execution. Key issues such as resource conflicts, interdependencies between projects, competing priorities, and communication breakdowns often arise, further complicating the planning process.

A significant problem in a multi-project environment is allocating and optimising shared resources. Project managers often need help balancing limited human and technical resources across several projects. This scenario can lead to resource bottlenecks, over-allocation, or under-utilization, adversely affecting project timelines, cost, and quality [2] and making it very difficult to meet the budget and schedule set by the stakeholders. While these challenges are significant, researchers have developed various solutions and techniques to address them. Projects often exceed the estimated time, budget, or quality [3].

Prominent methodologies, such as the Critical Path Method (CPM) and the Program Evaluation and Review Technique (PERT), traditionally operate under the assumption of unlimited resources and are typically applied to individual projects in isolation [4]. This limitation allows researchers to develop more effective approaches, including hybrid models integrating existing techniques and innovative methods such as machine learning (ML) algorithms. This paper explores the challenges associated with resource allocation in multi-project environments and evaluates current strategies to address these issues.

Study design

This study investigates the challenges of planning software projects in a multi-project environment. To guide this investigation, two research questions were formulated:

– What issues with resource allocation exist in a multi-project environment?
– What technologies are employed to resolve these resource allocation problems?

The first question aims to compile a list of the most analysed problems, while the second seeks to identify the most used techniques to address these issues.

To gather relevant literature, we conducted a search using the following query applied to the titles, keywords, and abstracts of articles in IEEE Xplore, ACM Digital Library, ScienceDirect, and Scopus: ("Index Terms" : "scheduling of multiple projects under resource constraints") OR ("Index Terms" : "multi-project scheduling"). The search was limited to articles published between 2008 and 2023, yielding 64 papers.

During the paper selection process, we refined the initial collection to exclude articles that did not fully align with the study objectives and removed duplicates. This resulted in a final dataset of 21 papers, all of which were published in English.

The work aims to comprehensively analyse the resource-constrained multi-project scheduling problem as explored in published research.

Statement of the primary material

Issues with resource allocation in a multi-project environment. Table 1 shows how the papers are classified, considering the group of the problem they belong to.

Table 1

Identified issues with resource allocation

Issue/problem	Frequency	Papers
Resource underutilisation/inefficiency	8	[5–12]
Long project duration	5	[13–17]
Project uncertainties and risk of delay	5	[7], [18–21]
Big project costs and penalties	4	[22–25]

The most problematic issues are resource under-utilisation, inefficiency, and conflict. [5] aimed to improve the resource utilisation rate to avoid re-source conflict in the manufacturing area. In the paper [6], upper and lower bounds allowed activities to run simultaneously and improve resource utilisation. [7] was focused on resource conflict resolution. They used project buffer and capacity constraint buffer for neighbouring projects. The goal of [8] was to minimise the total makespan of concurrently implemented projects and achieve maximum utilisation of resources. They considered every project makespan because it plays an essential role in the total delay of the projects. [9] aimed to maximise the efficiency of human resources by allocating the right people to suitable projects considering many factors. [10] tried to solve inefficient resource issues but needed to consider uncertain activity duration. In [11], coordinated planning and scheduling for efficient utilisation of constraint resources were explored on a high and medium level of planning horizon integrated. [12] was aimed at selecting the optimal solution for resource utilisation.

Next on the list was the long total duration of the multiple projects (makespan) [13]. The main objective was the minimisation of multi-project delay for large-scale construction projects. Babe et al. [14] considered minimising makespan as their primary objective. However, minimising project cost was also a critical matter, though a trade-off was required since time and cost often oppose each other. [15] contributed to minimising the makespan, but without considering the cost of resources. [16] minimised the project makespan by taking into consideration personality traits and skills. [17] aimed to optimise the expected project makespan within distributed resources and multi-skilled staff.

The authors of [18] applied the buffer management mechanism, which aimed to eliminate the uncertainties of the project. In [7], project activities were estimated in a fuzzy way with a safe time to solve the project uncertainties issue. [19] proposed a way of establishing project duration and project cost disturbances caused by the uncertain environment and considering them for project scheduling. In the paper [20], uncertain factors were the essential problem of the study. They used a proactive model for initial resource allocation and a reactive recovery strategy when the activity was interrupted. [21] also studied uncertainty in project implementation, but on a broader scale, when resources are distributed globally.

In [22], an approach was proposed to lower project costs and maximise the net profit for manufacturing projects while considering the early completion bonus, penalty cost, and resource costs. In [23], reducing project cost was one of two research goals (another one was reducing makespan to minimise the total time of all projects). [24] considered cost penalties if the project was not accomplished by the due date and was focused on reducing project costs. [25] aimed to minimise the adjustment cost of the multi-project schedule upon the arrival of a new project.

In conclusion, the authors emphasise minimising resource underutilisation, inefficiency, and conflicts in multi-project environments. Essential techniques include enhancing resource utilisation rates, establishing upper and lower bounds for activities, and resolving resource conflicts through buffer mechanisms. Efforts are also directed towards maximising the efficiency of human resource allocation. Additionally, minimising makespan is a primary focus, with considerations for project uncertainties, cost disturbances, and other uncertain factors. Approaches vary, with some prioritising the reduction of project delays and costs, while others aim to optimise the makespan within the context of distributed resources and multi-skilled staff. Cost considerations in these strategies include early completion bonuses, penalty costs, and minimising adjustment costs.

Technologies have been employed to resolve the problems with resource allocation. Many techniques have been used to fix the resource allocation problem (Table 2).

Table 2

Reported solving techniques for resource allocation problem

Techniques	Frequency	Papers
Heuristic algorithms	7	[6], [8], [11], [13], [17–18], [21]
Genetic algorithms	5	[10], [19-20], [22], [24]
Theory of Constraints / Critical Chain Method	4	[7], [11], [18], [23]
Mathematical model	3	[14], [16], [25]
Program Evaluation and Review Technique	2	[8], [18]
Ant colony algorithm	2	[15], [24]
Local search strategy	2	[10], [24]
Critical Path Method	1	[18]
Greedy strategy	1	[5]
Racoon family optimisation algorithm	1	[22]
Bee colonial algorithm	1	[22]
Combinatorial optimisation	1	[9]
Metaheuristic algorithms	1	[12]
Deep reinforcement learning	1	[12]

One of the most popular techniques to solve the issues of multi-project scheduling with resource constraints was using heuristic algorithms. [6] presented priority-rules-based heuristics, but they optimised it by setting lower and upper bounds for each activity's resource usage. In [8], the authors present a new approach based on a new heuristic two-level priority rule: maximum successors and minimum negative impact. The authors compared its performance with CPM, which caused resource conflict contrary to their approach. [11] proposed a drum buffer heuristic algorithm. Drum buffer is a direct application of the theory of constraints in which the drum is considered a capacity constraint resource. Stefanos [13] presented the single-pass parallel heuristic algorithm. It considered priority rules and resource overheads induced by resource transfers. [17] explored a heuristic-based approach with 12 priority rules and multiple scheduling stages for distributed multiple projects and multi-skilled staff. [18] used a heuristic algorithm based on the theory of constraints and PERT/CPM technology. Besides the project buffer and feeding buffer, they calculated the resources buffer to solve project uncertainties issues. [21] presented a multi-priority rule heuristic approach. They tested it on the multi-project scheduling problem library dataset, and it performed better than several competitive algorithms.

Another popular solution was using genetic algorithms (GA). In [10], the authors tried to address several problems with their multi-operator-based genetic algorithm, which was improved by a local search strategy to refine the solution and an automatic restart strategy to diversify the population. They achieved a bit better result, but their research had limitations. The paper [19] used a dual-population genetic algorithm to minimise the disturbance caused by uncertain factors. It took a rescheduling scheme calculated by project and cost disturbance and then a second stage to prevent the excellent population from being destroyed. [20] developed a genetic simulated annealing algorithm to solve multi-project scheduling problems under uncertain conditions. The simulated annealing process effectively controlled the convergence of the algorithm. The global optimisation ability was enhanced, and the algorithm's performance was improved. Mudassar et al. [22] developed an integrated approach using a raccoon family optimisation algorithm (RFO) for minimising project costs and maximising net profit. They considered renewable and non-renewable constraints, different release dates, and execution modes. RFO was compared with the genetic algorithm and bee colonial algorithm. RFO outperformed the other compared algorithms in terms of effectiveness and efficiency. Shih-Chieh [24] developed the ANGEL algorithm to minimise the project's cost. It included ant colony optimisation (ACO), GA, and local search (LS) strategy. ACO was used to generate activity lists, then passed into GA to create new lists, which LS improved.

The theory of constraints was not used purely; it evolved into the Critical Chain Method (CCM), which is also now used with optimisations. [7] presented a method CCM mixed with fuzzy logic to estimate activity durations to mitigate resource conflicts and project uncertainties. [23] used an optimised CCM for multiple projects to reduce makepan (and lower total time) and minimise project budget.

A couple of studies used different mathematical models to solve the issues with multi-project scheduling. [14] applied a mathematical model to find the optimal resource scheduling with minimum makespan at the lowest possible cost. Two priority rules were needed – one for activity selection and another for execution-mode selection. Then, constraints were applied. Finally, the objective function (minimising the total project lifespan) provided minimum completion time. [16] considered skills and personality traits for scheduling multiple projects. Their results showed that the algorithm performed better than the heuristic and that the makespan was smaller as resources were used more efficiently. In [25], mathematical models were used to minimise the project cost and the makespan but found optimal value in each in two stages.

Also, there were a lot of other approaches. ACO was applied in [15] but improved with a series schedule generation scheme and conflict resolution strategy to minimise the makespan. [5] pointed out that a single activity may require multiple resources and that resources can be deprived in practice. A scheduling algorithm based on a greedy strategy was described, which aimed to improve resource allocation and shorten the duration of both multi-projects and every single project. It also enhanced resource utilisation a bit. [9] used combinatorial optimisation, considering many constraints, to maximise the efficiency of human resources assigned to multiple projects, using experiments on actual data. [12] combined several meta-heuristic algorithms, such as discrete cuckoo search (DCS) and particle swarm optimisation, redefining the DCS algorithm's key steps. Additionally, deep reinforcement learning was used to select the best algorithm.

In conclusion, the findings of the second research question detail various techniques employed to address resource allocation challenges in multi-project scheduling with resource constraints. Widely used heuristic algorithms, such as priority-rules-based and drum buffer approaches, optimise resource utilisation and minimise project delays. GA also provide a popular solution, with research focusing on performance enhancements through multi-operator strategies, dual-population schemes, and simulated annealing techniques. Mathematical models and hybrid approaches, incorporating concepts like the CCM and ACO, are also explored to minimise project duration and costs. These diverse methodologies underscore the complexity of the multi-project scheduling problem and the necessity for innovative strategies to optimise resource allocation efficiently.

Discussion. Analysing the articles chronologically answered the research questions and illustrated how approaches have evolved from older to newer publications. Software project planning in a multi-project environment presents several challenges, mainly due to the NP-hard nature of the resource-constrained scheduling problem [26]. Balancing the minimisation of time and cost is particularly difficult since these factors often conflict [14].

Earlier papers predominantly focused on addressing these issues within construction and manufacturing sectors, often assuming certainty in activity size or disregarding the cost of resources and other constraints. Some of these solutions were highly specific and applicable only to large projects [17]. Techniques like PERT/CPM and constraint-based CCM were initially used but proved ineffective in multi-project environments. Consequently, newer papers are built on these methods, incorporating optimisations to address activity uncertainties, limited costs, and other constraints. However, their efficiency remained debatable due to the specificity of the constraints they supported [7].

Later, heuristic algorithms and GA became widely explored, aiming to generate ideal schedules that minimised makespan, cost, and resource conflicts. Heuristic approaches based on priority rules were extensively examined and frequently employed in research. Different papers utilised varying numbers of rules and buffers. The most advanced method [17] used 12 priority rules and multiple scheduling stages, successfully minimising project makespan. However, it was more effective on a large scale and less so on more minor instances and did not support uncertain environments where resources could be reallocated between projects. Additionally, heuristic algorithms, though commonly used, often lacked performance guarantees and could unknowingly underperform compared to optimal solutions [14].

GA faced challenges with population diversity, often converging to local optima instead of finding global ones. Their performance also suffered when complying with numerous constraints. Consequently, enhancements such as LS [10] and simulated annealing [20] were incorporated to improve performance and achieve better global optima. However, no single GA solution was universally applicable.

Mathematical models demonstrated promising results. For instance, [16] showed that their algorithm outperformed heuristic methods by using resources more efficiently to reduce makespan, though cost was not considered.

The most promising approach identified was the use of hybrid multi-stage techniques. For example, [12] employed deep reinforcement learning to select the best algorithm between heuristic swarm optimisation and cuckoo search. Multiple stages were then used to generate, refine, and optimise the initial schedule. ML techniques are becoming widely used in various spheres of human life [27]. They have significant potential in this area for determining the best approach in specific situations and addressing the resource-constrained multi-project scheduling problem more efficiently by leveraging historical project data.

Conclusions

This article presents a system analysis of papers published from 2008 to 2023 on the resource-constrained multi-project scheduling problem. After refining our selection, we analysed 21 relevant papers and identified various aspects of the issue along with numerous techniques for addressing it.

The analysis revealed that crucial issues include high project costs, lengthy makespans, uncertainties, and underutilised or conflicted resources. While various studies attempted to address these issues, none provided a comprehensive solution to all of them.

Thirteen different techniques were employed to tackle these challenges. Historically, these techniques evolved from pure solutions to hybrid approaches, combining various methods to mitigate the shortcomings of the base solutions.

The most promising direction for future research is the application of machine learning techniques, such as deep reinforcement learning, to find the best solutions for the resource-constrained multi-project scheduling problem. These advanced techniques can potentially consider all constraints and minimise time and cost while avoiding resource conflicts.

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