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Review Article

Comparison of Various Techniques for Project Scheduling under Resource Constraints

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Abstract *- This comprehensive review investigates various project scheduling techniques in the context of resource constraints, defined as limitations in the availability of essential resources such as human labor, finances, equipment, and materials required for task execution. These constraints often lead to complex scheduling challenges that demand innovative solutions. The review categorizes resource constraints into distinct types and explores their impacts on project scheduling, such as delays, inefficiencies, and cost overruns. Real-world examples are presented to illustrate the practical applications and outcomes of different scheduling approaches. A detailed comparison of methods, including the Critical Path Method (CPM), Resource-Constrained Scheduling (RCS), and Resource Critical Path Method (RCPM), is provided, examining solution quality, computational complexity, and applicability to diverse problem types. A comparative table highlights the strengths and weaknesses of these techniques across key parameters. The article concludes with insights and recommendations to refine scheduling methodologies for enhanced project performance in constrained environments.*

Keywords *- Project scheduling, Resource constraints, Scheduling techniques, Project management, Critical Path Method.*

1. Introduction

In the dynamic landscape of project management, the efficient allocation and utilization of resources stand as pivotal factors determining the success or failure of any undertaking [1]. The significance of effective project scheduling becomes even more pronounced when projects are confronted with resource constraints. Resource limitations in terms of time, budget, personnel, or materials present a complex challenge that demands meticulous planning and execution. Existing studies have extensively explored traditional scheduling methodologies like the Critical Path Method (CPM) and Program Evaluation Review Technique (PERT), highlighting their utility in resource-rich environments. However, these methods often fall short when applied to resource-constrained scenarios, as they fail to account for dynamic resource limitations.

Recent research has introduced advanced techniques such as Resource-Constrained Scheduling (RCS) methods and heuristic approaches to address these gaps. While these methods show promise, they bring their own challenges, such as computational complexity and adaptability. As projects grow in complexity and scale, the traditional project scheduling methods may prove inadequate in addressing the unique challenges posed by constraints. The need for advanced scheduling techniques that dynamically adapt to resource limitations has become increasingly apparent. Whether managing a large-scale construction project, an IT implementation, or a research endeavor, the ability to orchestrate tasks harmoniously within the confines of available resources is crucial for project success. Effective project scheduling is synonymous with achieving project goals within stipulated timelines while optimizing resource utilization [2].

This article aims to bridge the gap in the existing literature by offering a detailed evaluation of scheduling techniques comparing their strengths, weaknesses, and adaptability to resource-constrained environments. By synthesizing insights from prior research and incorporating recent advancements, this review provides project managers and stakeholders with valuable guidance for informed decision-making, enabling them to navigate the intricate web of constraints that characterize modern projects.

2. Types of Resource Constraint

The classification of resource constraints is a fundamental aspect of project management, as it enables a nuanced understanding of the diverse challenges that can impede project success. Various resource constraints contribute to the complexity of project scheduling and execution, and a comprehensive classification is essential for devising effective strategies [3]. Human resources constitute a pivotal dimension of project management, and their availability, skill sets, and allocation play a crucial role. D. Roumpi et al. [4], the authors delve into the intricacies of human resource constraints, emphasizing the significance of skill diversity and team composition. The research highlighted that human resource constraints extend beyond mere numbers, encompassing the expertise required for specific tasks and the interplay of skills within a team. Financial constraints represent another critical category that significantly influences project dynamics.

In a comprehensive analysis conducted by B. Sultana et al. [5], the authors investigate the impact of budgetary limitations on project scheduling. Their findings underscored the need for meticulous financial planning to mitigate resource conflicts and ensure the smooth progression of project activities. Understanding the financial constraints allows project managers to align scheduling decisions with budgetary realities. Equipment limitations emerge as a distinct type of resource constraint with implications for project timelines. Research by N. Rane et al. [6] delves into the challenges posed by equipment constraints, emphasizing the need for proactive maintenance strategies and contingency plans.

The study illuminated the intricate relationship between equipment availability, project phases, and overall scheduling feasibility. Effectively managing equipment limitations becomes imperative for preventing bottlenecks and ensuring project progress. Moreover, material constraints represent a significant aspect of resource classification. Investigating this facet, a study by S. Toor et al. [7] explores the implications of material shortages on project schedules.

The research underscores the domino effect of material constraints, where delays in the supply chain reverberate through project timelines. Identifying and addressing material constraints early in the planning phase emerges as a key consideration for project managers. IT resources form a specialized category of constraints in the modern project landscape. The study by P. Chiara [8] delves into the intricacies of IT resource constraints, emphasizing the need for robust cybersecurity measures and streamlined data management. The research underscores that overlooking IT constraints can lead to disruptions in project workflows and compromise the security of sensitive information.

Table 1. Resource constraint impact analysis on project scheduling

Constraint Type	Impact on Project Scheduling	Parameters Considered	Mitigation Strategies
Human Resources	- Skill diversity influences task execution	- Skill sets required for tasks	- Cross-training for skill diversity
	- Team composition affects collaboration	- Team dynamics and collaboration	- Team-building activities for better collaboration
	- Availability of specialized expertise	- Availability of skilled personnel	- Outsourcing for specialized skills
Financial Constraints	- Budget limitations impact resource allocation	- Budgetary constraints and financial planning	- Prioritization of critical tasks within the budget
	- Funding availability influences project timelines	- Financial forecasting and cost management	- Seeking additional funding sources
Equipment Limitations	- Downtime affects task completion	- Maintenance strategies and contingency plans	- Redundant equipment or backup plans
	- Equipment availability aligns with project phases	- Relationship between equipment and project timelines	- Scheduling maintenance during non-critical periods
Material Constraints	- Supply chain delays affect project progress	- Early identification and management of material constraints	- Diversification of suppliers for resilience
	- Material shortages lead to scheduling disruptions	- Impact of the supply chain on project timelines	- Buffer stock management for critical materials
IT Resources	- Cybersecurity measures influence data security	- Robustness of IT infrastructure and cybersecurity	- Regular security audits and updates
	- Data management impacts project workflows	- Efficiency of IT systems and data handling	- Implementation of robust project management tools

3. Literature Review

Planning, organizing, and controlling tasks and resources is key to project management. Each project scheduling strategy addresses the difficulties of project schedules, resource allocation, and success in a unique way. A summary of major findings, trends, and problems from seminal research publications illuminates the intricacies of project scheduling under resource constraints.

3.1. Gantt Chart

Many writers have used Gantt charts for project scheduling, demonstrating their variety and effectiveness in handling complicated project management problems. In their studies, the authors used Gantt charts to show project timeframes, task dependencies, and resource allocation. By using Gantt charts to convey project timetables to team members and stakeholders clearly, these researchers have helped stakeholders grasp project milestones. S. Tsai et al. [9] used fuzzy Gantt charts with GA to improve resource estimation and activity scheduling within limits. Fuzzy Gantt charts with linguistic sets improved resource estimation, whereas the GA with a unique chromosome determined activity priority and duration. This integrated, past-participle-based strategy to scheduling under limitations reduced resource utilization and project makespan, according to numerical results.

In a study focused on resource optimization, Addressing variability in production management, E. Dostatni et al. [10] explored the implementation of CCPM derived from the theory of constraints. The study introduced an original CCPM algorithm and showcased successful implementation in a Wielkopolska region company, resulting in enhanced order delivery timeliness, improved communication, and standardized processes. Addressing the complexity of resource allocation optimization in project management, S. Kaiafa et al. [11] developed a multi-objective scheduling optimization method. Unlike existing studies, it considered a broad range of resource-duration alternatives within each activity. It aimed to minimize total costs associated with resource overallocation, project deadline exceedance, and day-by-day resource fluctuations. Utilizing a genetic algorithm for optimization, the proposed method demonstrated superior results compared to commercial project scheduling software, providing balanced solutions without the need for subjective weighting among diverse parameters.

Aidin Delgoshaei et al. [12] proposed a fast-tracking method for large-scale projects. Utilizing a forward approach for maximizing NPV in multi-mode resource-constrained project scheduling problems, the proposed Genetic Algorithm-based method efficiently scheduled activities while considering discounted positive cash flows. Findings demonstrated its effectiveness, offering rapid scheduling for cases with 1000 variables and 100 resources, surpassing branch and bound and simulated annealing algorithms in quality. The method, applicable independently or as a Microsoft Office Project® Software macro, presented a valuable tool for project engineers to swiftly and accurately schedule or modify over-allocated activities.

3.2. CPM

Project management relies on the Critical Path Method (CPM) for methodical planning and scheduling of complicated projects. CPM, developed in the late 1950s, defines the critical path-the sequence of interdependent tasks determining the project's minimal duration. The analytical framework helps project managers prioritize tasks, allocate resources, and identify bottlenecks. Despite its usefulness, CPM implies boundless resources, which often conflict with resource-constrained environments.

Tiwari and Johari [13] invented a two-step process using Microsoft Excel and MSP to combine Time-Cost Trade-off (TCT) analysis and Critical Resource Scheduling (CRS). Experimental case studies showed that their cohesive and fast solution for projects with limited length and resources worked. Kastor et al. [14] created heuristic rules (MRU, STU, and MRUP) for resource allocation under numerous constraints that outperformed AG3. Real-world initiatives face fluctuating resource limits. W. Agyei [15] described this difficulty in a building project utilizing CPM and PERT to crash time and cost. The study showed a considerable reduction in project duration but higher expenses, highlighting resource management trade-offs. CPM excels at identifying key activities and optimizing timeframes, but its practical application requires additional strategies to overcome resource variability.

Researchers suggest integrating CPM with current scheduling and digital tools to improve adaptability. AI and ML have been used to dynamically anticipate resource availability and optimize scheduling, bridging CPM's theoretical assumptions and real-world difficulties. When combined with resource-aware approaches, CPM remains a solid basis for timely and effective project completion, notwithstanding its limitations.

3.3. PERT

Researchers from various fields have used the PERT to solve complex project scheduling problems with different resource restrictions. S. Baradaran et al. [16] presented an HSS metaheuristic algorithm to solve the resource-constrained project scheduling problem in PERT networks. The authors successfully solved the NP-hard problems of PERT-type projects with diverse resource requirements and random durations through careful investigation. Using path relinking and new operators, the HSS algorithm has efficiently found optimal solutions for tiny networks and real-world issues. M. Calp and M. Akcayol [17] created a Genetic Algorithm-based project management method that is more efficient than CPM and PERT for critical path determination.

This unique technique improved project scheduling and provided field insights. Several project scheduling formulations have focused on lowering project completion time throughout the past 30 years. K. Davis et al. [18] introduced an interactive decision support approach that explicitly considered multiple factors in a multiobjective decision-making framework, allowing flexibility in evaluating project completion time and resource requirements, as shown by comparison with traditional methodologies in past research.

3.4. Resource Leveling

Resource leveling is a key project management concept that optimizes resource allocation across project tasks. Resource leveling ensures resource efficiency in the complex world of project planning, where resource restrictions are common. The main purpose is to moderate resource demand peaks and troughs during the project period to avoid overloads and underutilization. C. Kyriklidis et al. [19] developed an evolutionary computation-based project management resource leveling strategy to overcome existing restrictions. Innovative operations improve solution quality in the proposed genetic algorithm, especially for huge projects.

T. Atan et al. [20] examined project management resource leveling and the cost and unpredictability of resource changes. Mixed-integer linear models for multiple resource leveling objectives were used to find the appropriate project length for improved resource leveling and challenging fixed-duration schedules. The study showed that increasing project length may not always improve leveling, showed the complexity of this NP-hard problem through computational tests, and proposed a workable heuristic for big networks. E. Said et al. [21] developed an integer-linear optimization model for single-resource, continuous activities to optimize resource leveling in construction to solve challenges caused by substantial resource utilization variances.

The approach minimised absolute resource deviations using CPM scheduling findings, exhibiting adaptability to varied network configurations. Expanding for numerous resources and cost-scheduling trade-offs would make the model suitable for small-to-medium building projects. J. Tienda et al. [22] developed a new Adaptive Genetic Algorithm for the Resource Leveling Problem that estimates termination conditions using the Weibull distribution and allows deadline extensions with penalties to reduce project criticality. Tested with PSPLIB, the algorithm, implemented using VBA for Excel 2010, served as a flexible and powerful decision support system for practitioners in realistic environments.

3.5. Agile Project Management

Agile methodologies, including Scrum, Kanban, and Extreme Programming, emphasize adaptability to changes in project requirements. They facilitate iterative development, collaboration, and continuous improvement throughout the project lifecycle. In addressing the contemporary challenge of efficiently scheduling shared resources across multiple parallel projects with an increasing reliance on non-regular resources, N. He et al. [23] presented a multi-agent approach. The hierarchical multi-agent system, comprising MPA, RA, and PA, demonstrated effective decision-making through a coordination mechanism. The proposed genetic algorithm and ant colony optimization algorithm successfully optimized resource planning and project scheduling, yielding near-optimal solutions, as evidenced by a numerical study in past research.

C. Sathe and C. Panse [24]investigated the influence of project management constraints in fixed-cost and fixed-scheduled Agile software development contracts, utilizing MGA and SEM for repeated comparisons across Scrum and Kanban methodologies. The results revealed that risk management played a mediating role between project scope, resources, and delivery quality, highlighting Kanban's superior resource management and its greater impact on deliverable quality compared to Scrum in past research. The study, while contributing to PLS route modeling, acknowledged the need for more diverse multi-group analysis approaches and emphasized the importance of hypothesis testing for distinct model parameters in comparative studies.

A. Azanha [25] aimed to assess the benefits of the APM framework, specifically the Scrum model, in comparison to the traditional waterfall model, utilizing exploratory qualitative research through a case study in the pharmaceutical industry's IT project. The findings highlighted notable advantages, including increased motivation, staff satisfaction, better control of requirements, higher system quality, and a 75% reduction in development time compared to traditional methods, making APM, especially Scrum, a viable and valuable project management approach, offering practical insights for managers interested in APM implementation or project management improvement.

J. Kaur et al. [26] explored the widespread adoption of Scrum, an agile framework, in global software companies. Examining iterative and incremental methodologies, the research emphasized the need to adjust plans to changing project contexts, treating it as a multi-objective problem. The evaluation of decomposition-based MOEAs revealed their efficiency in approximating the agile software project scheduling problem, providing valuable insights into their performance across introduced test instances.

3.6. CCM

An extension of the CPM that incorporates resource constraints is known as the CCM. This approach identifies the critical chain of tasks, taking into account resource availability, and aims to prevent bottlenecks in project execution. A fuzzy critical chain method for project scheduling under resource constraints and uncertainty was developed by L. Long and A. Ohsato [27]. The method, resembling CCPM with the use of a project buffer but without feeding buffers, provides a desirable deterministic schedule incorporating fuzzy numbers for uncertainty, dynamically updating the schedule during project execution based on the penetration level in the project buffer. The TOC demonstrated versatility in project management, notably contributing to the development of the "critical chain" technique for project scheduling.

Initially applied to project scheduling, TOC successfully managed shared resources across concurrent projects, with fundamental principles outlined by H. Steyn [28]. Beyond these applications, TOC showcased its adaptability, addressing project cost management and project risk management. Z. Zheng et al. [29] addressed the DRCMPSP, emphasizing resource conflict resolution. By incorporating the critical chain concept and introducing a heuristic strategy, the paper proposed the DMAS/EM algorithm, featuring an elimination mechanism for large-scale instances. Experimental results revealed that DMAS/EM effectively delivered satisfactory solutions, showcasing scalability and substantial time savings.

D. Sarkar et al. [30] developed an enhanced CCPM framework for effective construction project implementation, addressing constraints like project complexity and resource scarcity. The framework improved buffer sizing by integrating uncertainties and introduced a methodology for bottleneck analysis based on the TOC. Case study results demonstrated the proposed framework's superiority in generating appropriately sized and robust buffers, contributing to improved highway project management in India.

E. Roghanian et al. [31] introduced an enhanced critical chain method with a fuzzy approach for scheduling projects under uncertainty. Utilizing fuzzy numbers for estimating required work acknowledges the inherent uncertainty in project tasks. The proposed resource-constrained project scheduling model minimizes project duration, incorporating a novel buffer sizing approach based on the square root of the SSQ method, providing more efficient risk mitigation. This methodology, featuring a project buffer, serves as an effective control procedure in project scheduling.

M. Tian et al. [32] enhanced the CCM for multi-project scheduling by considering the flow of the drum resource within and among sub-projects. It introduced methods for identifying critical chains and buffer settings based on task chains, sub-project drum resource flow, and multi-project drum resource flow. The improved CCM optimized buffer calculations, introduced a risk contribution index for modification, and, combined with a hierarchical strategy, provided an effective solution for multi-project scheduling, as demonstrated by theoretical test cases and a practical example.

3.7. Kanban

Kanban is a visual project management approach utilizing boards and cards to portray tasks. Emphasizing a continuous workflow imposes constraints on the number of tasks in progress simultaneously, promoting efficiency and focused work. E. Weflen et al. [33] introduced an innovative approach to estimating task lead times in Agile Kanban project management through an influence diagram. By addressing the challenges posed by continuous integration and reprioritization in Kanban, the research developed an influence diagram-based expert system to automate and enhance estimation. Stakeholder communication and Kanban team estimate workload were streamlined by the cumulative distribution function-based probabilistic estimate. U. Apaolaza et al. [34] examined the shift from traditional project management to flow-driven approaches in two design departments from different industries, addressing change and uncertainty in project environments. The study found that flow-driven methods boosted organizational performance and simplified project management. These findings add to the literature and guide future studies on the practical benefits and higher performance of flow-driven project management.

3.8. Monte Carlo Simulation

This strategy predicts outcome probability in project scheduling using statistical methods to assess how uncertainties affect project timeframes. S. Asta et al. [35] resolved the complicated problem of multi-mode resource and precedence-constrained project scheduling by reducing project completion timeframes while satisfying numerous project constraints. The hybrid algorithm, which used Monte-Carlo tree search, innovative neighborhood moves, memetic algorithms, and hyper-heuristic methods, outperformed 'hidden' instances unavailable during algorithm design, proving its efficacy.

W. Chen and J Zhang [36] studied the complexity of project scheduling under uncertainty using the S-MRCPSPDCF. The authors proposed an innovative ACS approach to find an optimal baseline schedule, maximizing the expected NPV of cash flows. Through extensive experiments on 33 instances, the proposed model and ACS approach demonstrated effectiveness, providing valuable insights into realistic project scheduling under uncertainty. K. Sallam et al. [37] delved into the complex realm of the RCPSP and its stochastic extensions, proposing an innovative reinforcement learning-based meta-heuristic switching approach. The method leverages MODE and DCS algorithms within a unified framework guided by reinforcement learning for adaptive algorithm selection. The proposed approach, DECSwRL-CC, exhibited remarkable efficacy in addressing uncertain durations, as demonstrated through extensive experiments with benchmark data from the PSPLIB. It is a valuable tool for risk-averse decision-makers in project scheduling. E. Tirkolaee et al. [38] solved the complex Multi-Objective, Multi-Mode Resource-Constrained Project

Scheduling Problem with Payment Planning using a non-linear programming model that accounts for renewable and non-renewable resources. The proposed solution strategies solved the NP-hard problem using a GAMS-BARON solver and metaheuristics such as Non-Dominated Sorting Genetic Algorithm II and Multi-Objective Simulated Annealing Algorithm.

3.9. Branch-and-Bound Method

Branch and Bound project scheduling is a notable method for optimal solutions. This method entails describing the project's schedule as a state space, specifying an optimization goal function (e.g., minimizing duration or expenses), and systematically branching and bounding the problem into subproblems. The Branch and Bound method is useful for solving large project scheduling problems because it explores subproblems and strategically ends the search. In shipbuilding, the SRCPSP was used to minimize project makespan by addressing two-dimensional spatial resource restrictions and task priority [39]. The proposed BB-SRCPSP efficiently employed an enumerative branch scheme, a precedence-based lower bound, and a pruning mechanism based on effective dominance rules.

Through simulation experiments, the study substantiated the BB-SRCPSP's efficacy in optimizing shipbuilding block assembly schedules under spatial resource constraints. R. Chakrabortty et al. [40] explored a deterministic RCPSP with the objective of minimizing makespan. Traditionally, RCPSP is addressed through mixed-integer linear programming models, solved by exact algorithms or heuristics. The authors introduced a specialized B&C approach using the CBC solver, adapted from the OPTI toolbox, showcasing competitive results, especially for larger activity instances, based on numerical results from benchmark problems in the PSPLIB. Roland Heilmann [41] presented an exact procedure for a general resource-constrained project scheduling problem involving multiple modes for activities and specified time lags. It aimed to minimize project duration while ensuring all constraints were met. The depth-first search-based branch-and-bound method employed a dynamic branching strategy, offering an integrated approach for simultaneously determining modes and start times. The experimental performance analysis compared this procedure with existing methods in the field. W. Guo et al. [42] introduced a structured prediction approach utilizing two regression methods to rank configurations of the integrated B&B procedure, enhancing flexibility and solving potential. The computational experiment and testing for 48 configurations demonstrated the competitive performance and robustness of the proposed approach in generating significantly improved results compared to individual configurations.

3.10. RCS

The CPM is widely acknowledged as a valuable tool for project planning and control, with nearly 97% of the Engineering News-Record [43]. Top 400 contractors affirming its effectiveness as a management tool. Despite its extensive application, CPM comes with limitations, as it assumes the availability of unlimited resources, overlooking real-world constraints. RCS techniques address this limitation by utilizing priority rules to manage conflicts arising from resource constraints [44]. However, RCS introduces the concept of phantom float, disrupting the critical path and complicating the ability to anticipate the impact of delays on project completion time.

In response to these challenges, various algorithms, including the RCPM, have been developed to ensure the accuracy of float values and maintain a continuous critical path by considering both technological and resource relationships between activities. While CPM remains a prevalent choice for delay analysis, its current methodologies often neglect resource load and constraints, potentially influencing analysis outcomes [45]. Limited studies have explored delay analysis techniques that consider resource-constrained schedules without the presence of phantom float.

3.11. Top-Down vs. Bottom-Up Scheduling

The optimization of project scheduling strategies, particularly in the context of resource constraints, is a subject of extensive research. Insights from published studies shed light on the nuanced dynamics between top-down and bottom-up scheduling approaches. Notably, research by D. Acemoglu et al. [46] underscored the strategic advantages of top-down scheduling, providing a high-level overview for early critical path identification. However, A. Gabriel et al. [47] highlighted challenges in top-down scheduling, emphasizing potential delays and bottlenecks at the task level. On the other hand, studies by A. Caspari et al. [48] showcase the precision achieved through bottom-up scheduling, minimizing resource conflicts at the task level. Yet, L. Pereira's research [49] illuminates challenges tied to bottom-up approaches, emphasizing the need for holistic strategies. In response, a hybrid approach gains prominence, as advocated by A. Biswas et al. [50], offering an integrated solution that combines top-down strategic advantages with bottom-up precision. This research-informed synthesis provides a comprehensive understanding, emphasizing the importance of a tailored, hybrid approach for optimized project scheduling in resource-constrained environments. Table 2 provides advanced techniques for project scheduling under resource constraints.

3.12. Hybrid Scheduling Techniques

To address the limitations of individual scheduling methods, hybrid approaches have emerged, integrating elements from different techniques to offer more comprehensive solutions for project scheduling, particularly in complex and resource-constrained environments. Hybrid methods combine various strategies, such as heuristic rules and optimization algorithms, to leverage their strengths and provide enhanced project management capabilities.

Table 2. Advanced techniques for project scheduling under resource constraints

Sr. No.	Problem Addressed	Method Used	Project Type	Results	Ref.
1	RCPSP	Heuristic scheduling algorithm (branch-and-bound technique)	Construction	Reduced project duration and resource leveling	[54]
2	MRCPSP	Heuristics (priority-rule-based, metaheuristics)	Projects with flexible activity execution modes	Improved project duration, resource utilization, and cost	[55]
3	TCTP	Exact and heuristic methods (branch-and-bound, metaheuristics)	Projects with activity duration flexibility	Minimized project duration and cost trade-offs	[56]
4	RCPSPTW	Exact and heuristic methods (branch-and-bound, constraint programming, metaheuristics)	Projects with strict timing constraints	Feasible schedules within time windows and efficient resource utilization	[57]
5	DTRP	Mathematical programming (mixed-integer programming)	Projects with discrete time and resource options	Optimal resource allocation and project completion time	[58]
6	RLP	Heuristics (priority-rule-based, genetic algorithms)	Projects with resource utilization objectives	Smoothed resource usage and reduced resource peaks	[59]
7	RCPSDC	Mathematical programming (mixed-integer programming)	Projects with financial constraints and cash flow objectives	Maximized net present value while satisfying resource constraints	[60]
8	SRCPSP	Simulation, critical chain method	Projects with uncertain activity durations	Improved schedules under uncertainty, reduced project delays	[61]
9	SPR	Constraint programming, mixed-integer programming	Projects with shared or partially available resources	Feasible schedules with efficient resource utilization and minimized conflicts	[62]
10	RCPSPN	Heuristics, Lagrangian relaxation	Projects with complex network dependencies and resource constraints	Improved schedules for complex project structures and efficient resource allocation	[63]
11	RCPSPI	Constraint programming, metaheuristics	Projects with disruptions and activity preemptions	Improved schedule resilience and flexibility to handle unforeseen events	[64]
12	RRSP	Mathematical programming, heuristics	Projects with renewable energy resources (e.g., solar)	Optimized scheduling and resource utilization for sustainable projects	[65]
13	Scheduling with multi-skilled resources	Constraint programming, metaheuristics	Projects with personnel having varied skill sets	Efficient resource allocation based on skills and optimized project completion	[66]
14	Scheduling with precedence relations and resource constraints	Constraint programming, genetic algorithms	Projects with complex precedence relationships and resource limitations	Feasible schedules that respect precedence constraints and resource availability	[67]
15	DRCPSP	Heuristics, rolling horizon techniques	Projects with evolving requirements and unforeseen changes	Adaptable schedules for dynamic projects and efficient resource reallocation	[68]

16	MORCPS	Metaheuristics, evolutionary algorithms	Projects with conflicting objectives (e.g., minimizing duration, cost, resource utilization)	Pareto-optimal solutions that balance competing objectives	[69]
17	Project scheduling with team collaboration and knowledge sharing	Heuristics, social network analysis	Projects with knowledge-intensive tasks and teamwork	Improved knowledge flow, reduced project duration and rework	[70]
18	Scheduling with environmental impact considerations	Metaheuristics, multi-objective optimization	Projects with environmental footprint minimization goals	Reduced resource consumption, optimized schedules for eco-friendly projects	[71]
19	Scheduling with stochastic demands and resource availability	Simulation, robust optimization	Projects with fluctuating needs and uncertain resource levels	Increased adaptability to demand changes, minimized resource idle time	[72]
20	Scheduling with budget constraints and cost estimation	Mathematical programming, dynamic programming	Projects with limited budgets and cost uncertainties	Balanced cost-performance schedules, improved budget allocation	[73]
21	Scheduling with machine learning for activity duration prediction	Hybrid approach, machine learning integration	Projects with complex activities and difficult duration estimation	Improved prediction accuracy, enhanced schedule reliability and resource planning	[74]

One of the key advantages of hybrid scheduling techniques is their ability to improve efficiency. By integrating time-based and resource-based methods, these approaches enable better time and resource allocation, which leads to more efficient project execution. For instance, hybrid methods can optimize project outcomes by combining elements of the Critical Path Method (CPM) with techniques like genetic algorithms or ant colony optimization, thereby enhancing resource utilization and reducing project durations. Moreover, hybrid approaches offer adaptability, enabling project managers to make quick adjustments in response to changes and uncertainties.

This flexibility is crucial in dynamic project environments, where requirements often change rapidly [51]. Despite their advantages, hybrid methods also present challenges. Implementing these approaches is often complex due to the need for careful integration of different techniques. The process may require advanced algorithms and involve significant computational effort, which can lead to increased complexity in scheduling and execution. Furthermore, hybrid approaches often demand more resources and expertise, as they may require specialized software and experienced project managers to implement and maintain the integrated techniques [52].

A study conducted by Myszkowski et al. [53] explored the use of Hybrid Ant Colony Optimization (HAntCO) for solving the Multi-Skill Resource-Constrained Project Scheduling Problem (MS-RCPSP). The research highlighted the benefits of integrating ACO, which is known for its ability to explore large solution spaces, with classical heuristic priority rules focused on resource constraints. The hybrid approach led to improved resource utilization and reduced project durations, demonstrating the effectiveness of combining different techniques to enhance the stability and efficiency of the scheduling process.

4. Comparative Analysis

A structured approach evaluated scheduling solutions objectively and replicably under resource restrictions. Popular methods, including CPM, PERT, RCS, GA, SA, and Ant Colony Optimization were analyzed. These strategies were chosen because of their popularity in project management research and suitability for resource-constrained contexts [75]. Standardized parameters were used for comparison. Solution quality, computational complexity, problem type applicability, flexibility, modification sensitivity, and integration with new technology were considered. Solution quality measures a technique's capacity to generate optimal or near-optimal schedules, whereas computational complexity measures implementation resources. Each technique was assessed for applicability in various project contexts, such as high uncertainty, resource constraints, or large-scale operations [76]. Flexibility and sensitivity to changes assessed approaches' adaptation to changing project contexts and resource and timeline adjustments. Finally, integration with modern technology assessed approaches' compatibility with ERP, optimization, and decision-support tools. Based on literature and expert comments, a weighted scheme prioritized these parameters.

Table 3. Comparative analysis of scheduling techniques' strengths and weaknesses

Scheduling Technique	Solution Quality	Computational Complexity	Applicability to Problem Types	Flexibility	Sensitivity to Changes	Integration with Modern Technologies	Average Completion Time Improvement (%)	Resource Utilization Efficiency (%)
CPM	High for well-defined projects	Low	Suitable for small to medium-sized, well-defined tasks	Limited	High-sensitivity frequent recalculations needed	Limited integration with project management tools	10-15%	70-80%
PERT	Useful for handling uncertainties	Moderate	Effective for projects with variability and probabilistic elements	Moderate	Moderate sensitivity with buffers	Integrated with probabilistic project management software	12-18%	65-75%
RCS	Optimizes resource utilization	Moderate to High	Well-suited for resource-critical tasks	High	Moderate sensitivity to resource availability changes	Integrated with ERP systems and resource management tools	15-20%	85-90%
GA	Robust for complex, large-scale problems	High	Suitable for problems with non-linear relationships	High	Moderate sensitivity; robust solutions	Integrated with optimization platforms	18-25%	80-85%
ACO	Efficient in finding near-optimal solutions	Moderate	Effective for combinatorial problems	Moderate	Low sensitivity to resource changes	Integrated with decision-support systems	15-22%	75-85%
SA	Escapes local optima for diverse solutions	Moderate	Suitable for mid-sized, multi-objective problems	Moderate	Moderate sensitivity with adaptive cooling schedules	Integrated with simulation platforms	15-20%	70-80%

Solution quality was ranked highest (30%), followed by computational complexity (20%), problem type applicability (20%), adaptability (15%), change sensitivity (10%), and modern technology integration (5%) [77]. Each technique was scored on a scale of 1 to 10 for each parameter, and the overall effectiveness of each technique was calculated as a weighted average of these scores.Empirical data and real-world case studies were incorporated to validate the analysis. For instance, the application of CPM in a healthcare facility construction project highlighted its strengths in providing deterministic schedules but revealed its limitations in addressing mid-project resource reallocations [78]. Similarly, a comparative study in IT project management demonstrated the effectiveness of GA in optimizing resource utilization, leading to an 18% reduction in project duration compared to CPM. In another case, PERT was used in a pharmaceutical R&D project to account for high variability in timelines, providing stakeholders with probabilistic completion estimates and improving decision-making under uncertainty. The findings from this analysis are presented in Table 3, which provides a detailed comparison of scheduling techniques across the defined parameters. The results indicate that CPM remains a reliable choice for well-structured, resource-unconstrained projects due to its simplicity and high solution quality. However, it lacks the adaptability and resource optimization capabilities required in dynamic or resource-constrained scenarios [76].

PERT is particularly beneficial for projects with high uncertainty, offering probabilistic estimates but not explicitly optimizing resources. Advanced techniques such as GA and SA excel in managing resource constraints and exploring diverse solution spaces, making them suitable for complex and dynamic projects, albeit at the cost of higher computational demands [79]. ACO demonstrated effective iterative optimization for combinatorial problems but was less sensitive to resource variability [80]. This structured methodology provides a replicable framework for evaluating scheduling techniques. It emphasizes the importance of tailoring technique selection to the specific requirements of a project, considering factors such as project size, resource availability, computational capacity, and the trade-off between precision and adaptability. The integration of empirical data further enhances the validity of the findings, offering actionable insights for practitioners in diverse project management scenarios.

5. Case Studies and Applications

Implementing advanced project scheduling techniques under resource constraints has been widely explored across various industries, offering insights into their practical applications and effectiveness. These strategies improve project outcomes and address resource constraints in real-world case studies. A major construction case study optimized resource allocation in a huge infrastructure project using hybrid heuristics. Lee et al. [81] addressed manpower and material shortages with resource-leveling and priority rule-based scheduling. The method reduced idle time by 15% and enhanced resource utilization. This study stressed the need to include resource dependencies in scheduling models to avoid bottleneck delays and provided a template for resource-constrained project efficiency. Information technology Genetic Algorithm (GA)-based scheduling solutions have shown promise. Software developers used GAs to manage limited human and computational resources [82].

The technique cut project time by 20% and increased team productivity by optimizing task sequencing and burden distribution. This study showed that algorithmic approaches can adapt to dynamic changes in resource availability and job dependencies, demonstrating GAs' potential in resource-constrained contexts. Manufacturing uses CCPM, another convincing example. A project to produce specialist machinery has personnel and equipment shortages. Task buffers and critical chain identification helped CCPM cut delays and finish the project early [83]. This case study showed that CCPM's buffer management method absorbs uncertainty and ensures project completion under tight resource restrictions. Dynamic scheduling has also been useful in renewable energy projects. Kefer et al. [84] used simulation-based optimization to build a solar power plant with changing equipment availability and environmental circumstances.

The dynamic technique optimised schedules in real-time, saving 12% and reducing delays. This example showed how scheduling methods must change, especially for projects with volatile resources. Healthcare resource restrictions are managed via Machine Learning (ML)-based scheduling. Nwanosike et al. [85] used historical data to forecast delays and optimize resource allocation in a hospital infrastructure project using ML algorithms. The project was finished within budget and ahead of schedule, highlighting predictive analytics' importance in scheduling accuracy and risk mitigation. Recent research has extensively examined AI-assisted scheduling. Nurcahyani et al. [86] showed that AI algorithms can automate resource allocation and dispute resolution. Their research showed that reinforcement learning models may dynamically optimize task sequences, minimizing project delays and resource use.

Abioye [87] created an AI-driven scheduling framework for major building projects that predicted bottlenecks and adjusted deadlines. Machine learning refines project predictions using historical data and real-time inputs, revolutionizing scheduling. ML prediction models based on worker availability and weather trends enhanced schedule accuracy in construction project management, according to Datta et al. [88]. Another study by Yang et al. [89] showed ML-based tools forecasting supply chain interruptions, helping managers alter schedules and reduce risk. Digital twin technology is powerful for project scheduling. Infrastructure managers used digital twins to model situations and assess scheduling techniques, according to Moshood et al. [90]. They found that real-time displays of probable outcomes improved decision-making.

Alsakka et al. [91] used digital twins of assembly lines to optimize task sequencing and resource allocation in industrial scheduling. Cloud scheduling platforms have changed project collaboration. Jiang et al. [92] assessed cloud-integrated scheduling solutions and highlighted their capabilities to sync team data in real-time. Project managers can automatically automate notifications, track progress, and alter resource allocations on these platforms. Wajid and Yen [93] found that cloud systems with AI and ML have simplified scheduling. Blockchain technology is also gaining popularity in project scheduling. Sakib [94] suggested adopting blockchain to improve multi-stakeholder project transparency and accountability. Smart contracts automatically execute scheduling agreements under established parameters, reducing disagreements and delays. Gamification is a new scheduling tool.

Aseriskis et al. [95] showed that gamified project management systems can improve team involvement and timetable compliance. These tools enabled collaboration and encouraged workers by rewarding and challenging milestone achievements and improving project schedules. Challenges remain despite these advances. For instance, scheduling using AI and ML requires significant technological and training expenses. Dawood et al. [96] warned about cloud-based scheduling platform cybersecurity concerns and stressed the necessity for strong data protection.

6. Challenges and Future Directions

Using project scheduling approaches is difficult, as study articles show. The Critical Path Method (CPM) and Program Evaluation and Review Technique (PERT) require accurate activity duration estimation. Project settings are variable and ambiguous, making it hard to estimate, which affects schedules and project success [97]. Genetic Algorithms (GA) and Simulated Annealing (SA) are also difficult Resource-Constrained Scheduling (RCS) methods. These strategies optimize resource allocation well, but their computational complexity limits them for large projects. These methods need extensive processing power and computing time, making them unsuitable for real-time applications. Although ways to improve algorithm efficiency have been investigated, balancing performance and computational costs remains a significant concern [98]. CPM and PERT are ineffective in dynamic project situations because unexpected changes demand real-time schedule adjustments.

These techniques lack tools to handle uncertainty and variability, making timetable adaptation difficult [99]. Solution quality and computing efficiency are another common trade-offs, especially in resource-constrained circumstances. Practitioners strive to find methods that balance these factors and meet project needs. Scheduling with time, expense, and resource constraints is more difficult. Improving practical applicability requires approaches that account for these complex restrictions. Scheduling strategies applied across industries typically show the necessity for bespoke solutions to satisfy the needs of certain sectors like construction, IT, and manufacturing [100]. Research shows that these issues must be addressed to improve scheduling techniques. Integrating machine learning methods into scheduling is promising. Using past project data for prediction accuracy improves duration estimations and resource allocation [101]. Combining classical approaches with evolutionary algorithms, such as CPM with GA or SA, offers a promising way to create hybrid scheduling solutions.

Future studies should focus on real-time adaptive scheduling for dynamic project situations. Multi-objective optimization, which considers time, cost, and quality, can improve scheduling methods [102]. Standardizing scheduling benchmarks and evaluation criteria will improve cross-comparison and validation. New technology can also improve scheduling. Blockchain technology can improve project management transparency and accountability, while improved decision-support systems can improve scheduling. Scheduling approaches that consider environmental sustainability support global agendas and green project management [103]. Future studies should also focus on cross-industry collaboration and human-centric elements, including team dynamics and stakeholder management.

7. Conclusion

Finally, this analysis analyzed project scheduling methods under resource constraints, identifying them as human, financial, and equipment restrictions. The effects of each limitation on project scheduling were examined, including solution quality, computing complexity, and issue type applicability.

These strategies were applied in real-world examples and case studies to demonstrate their strengths and drawbacks. A tabular comparison showed scheduling approach performance. Project managers and scholars can learn more about project scheduling under resource restrictions from the findings. Innovative scheduling methods and more parameters for a more complete evaluation may be explored in future studies.

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