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THE MULTI-SKILLED RESOURCE-CONSTRAINED PROJECT SCHEDULING PROBLEM: A SYSTEMATIC REVIEW AND AN EXPLORATION OF FUTURE LANDSCAPES

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Abstract:
The Multi-skilled Resource Constrained Project Scheduling Problem (MS-RCPSP) is a complex and multi-faceted problem that involves scheduling activities whilst considering various resource constraints. These constraints include limited availability of workers, equipment, and materials, with each activity requiring a minimal set of skills to be executed. Furthermore, for a better resemblance to reality, workers/machines are assumed to be multi-skilled/multi-purpose posing another dimension of complexity to the problem. The objective is to minimize project duration, cost, or other relevant criteria while accounting for the inherent resources flexibility. This paper provides a systematic review of the literature pertaining to MS-RCPSP, and an in-depth analysis of 171 papers published between 2000 and 2021 inclusive. The conducted bibliometric analysis identifies the top contributing authors, most influential papers, existing research tendencies, and thematic research topics within the field. In addition, this review highlights different aspects of the MS-RCPSP, spanning the significance of performance measures, solution approaches, application areas, and the incorporation of time constraints. While project completion time, cost, and tardiness are common performance indicators, other measures such as multi-skilled staff assignment and schedule robustness are also deemed important. Although various methods have been employed to solve the MS-RCPSP including exact and approximate approaches, the selection of the most-suited approach depends on the problem's scale, complexity, and constraints, necessitating careful consideration of each method's strengths and weaknesses. Interestingly, several studies have jointly addressed resource and time constraints in the context of MS-RCPSP, often considering tardiness, and have proposed different algorithms, models, and metaheuristics to tackle these challenges. This paper clearly highlights research gaps and promising avenues for future research. This work provides valuable insights for project managers to effectively schedule tasks in the presence of multiple flexible resources.

Key words: Multi-skilled, Resource Constrained, Project Scheduling, Bibliometric Analysis, Network Analysis, Review

List of acronyms
AC: Automation in Construction
AI: Artificial Intelligence
ASCJ: Applied Soft Computing Journal
CD: Control and Decision
CIE: Computers and Industrial Engineering
Cmax: Completion Time
CP: Constraint Programming
CPU: Central Processing Unit
EJOR: European Journal of Operational Research
ESA: Expert Systems with Applications
FRWBIP: Flexible Resource Workload Balancing and Investment Project Scheduling Problem
GA: Genetic Algorithms
Gephi: A network analysis software
GVNS-PR: General Variable Neighbourhood Search-based Path Relinking Algorithm
HBD: Hybrid Benders Decomposition
IJAMT: International Journal of Advanced Manufacturing Technology
IJPR: International Journal of Production Research
IoT: Internet of Things
IS: Information Sciences
IT: Information Technology
LNCS: Lecture Notes in Computer Science
MIP: Mixed-Integer Programming

MILP: Mixed-Integer Linear Programming
ML: Machine Learning
MM-RCPSP: Multi-Mode Resource Constrained Project Scheduling Problem
MS-PSP: Multi-Skilled Project Scheduling Problem
MS-RCPSP: Multi-Skill Resource-Constrained Project Scheduling Problem
NP-hard: Non-deterministic Polynomial-time hard
PSPLIB: Project Scheduling Problem Library
RAIRO-OR: RAIRO Operations Research
RCPSP: Resource-Constrained Project Scheduling Problem
SC: Soft Computing
TCPSP: Time Constrained Project Scheduling Problem
TLBO: Teaching-Learning-Based Optimization
VNS: Variable Neighborhood Search
VOSViewer: A software tool for constructing and visualizing bibliometric networks

INTRODUCTION

In essence, scheduling refers to the process of planning and organizing activities, tasks and/or events in a structured manner toward ensuring that they are completed efficiently and effectively. In reality, scheduling is crucial to the success of a project or operation, as it helps ensure that resources are allocated in the most efficient way possible. A typical project scheduling problem includes a list of interrelated project activities, an estimate of each activity's duration, the consumable and renewable resources required for each activity, and the precedence relationships amongst the activities. The objective then is to devise a plan detaining the start and end time for each task, the resources allocated to each, while adhering to the existing dependencies between these tasks. Effective project scheduling is of paramount importance as it facilitates timely completion of projects, while abiding by the available budget and adhering to the required quality standards.

In principle, project scheduling problems are mainly categorized into Resource Constrained Project Scheduling Problems (RCPSPs) and Time Constrained Project Scheduling Problems (TCPSPs). The TCPSP is a well-known problem in the project management literature which involves scheduling a set of tasks or activities, subject to precedence relations and temporal limits. The objective then is to complete all tasks comprising the project within the agreed-upon deadline (e.g. handover date of the project) while achieving a smooth utilization profile of the resources during the project's life span (in what is commonly referred to as the resource levelling problem). In principle, the resource smoothing/levelling problem specifically deals with the challenge of allocating these limited resources in a way that minimizes fluctuations in their usage over time. It's a complex problem, even for a single resource case, and is known to be NP-hard (as noted in [1]). On the other hand, RCPSP refers to a type of project management problem in which the scheduling of tasks is constrained by limited resources. In other words, the RCPSP involves allocating limited resources such as equipment, personnel, or funds, to a set of tasks that make up the project. The objective of the RCPSP is to develop a schedule of all activities that can optimize the utilization of limited amount of resources and minimize the overall duration of the project. The RCPSP has received a lot of attention for several decades and is recognized for being a difficult optimization problem (also NP-hard as shown in [2]). Over time, various versions of RCPSP have been introduced, such as multi-mode RCPSP, RCPSP with time windows, and multi-skilled RCPSP, with the latter being the topic addressed in this paper.

Hartmann and Briskorn [3] conducted a survey of variants and extensions of the RCPSP. The multi-mode RCPSP (MM-RCPSP) is a variant of the RCPSP where each activity or task in the project can be executed in multiple modes or ways. Each mode has its own duration and resource requirements, which can differ from other modes for the same task [3]. On the other hand, RCPSP with time windows is another variant of the RCPSP where each activity has a specific time window in which it can be executed. The time windows can be defined as either fixed or flexible, meaning that the start and end times of the activity can be adjusted within a certain range. The objective of this variant is to schedule the activities while taking into account the resource constraints such as limited availability of labour, equipment, and materials, in order to minimize the project duration while meeting the specified time window for each activity [3].

Multi-skilled RCPSP (MS-RCPSP) is another variant of the RCPSP wherein each activity requires a set of skills to be performed [4]. Each skill is associated with a different worker or resource (or possibly more than one), and each worker can have multiple skills (or alternatively machines/equipment are general purpose ones). The goal of this variant is to schedule the activities while taking into account the resource constraints such as limited availability of workers, equipment, and materials, in order to minimize the project duration. The challenge in MS-RCPSP is to assign the most appropriate worker with the required set of skills to each activity, while considering the resource constraints and minimizing the overall project duration.

In principle, multi-skilling is the capability of employees to perform tasks beyond their job requirements giving an organization a competitive advantage and a much-needed flexibility to meet its goals. It is increasingly becoming a favoured business strategy due to its advantages for both employees and companies. Multi-skilled employees can benefit from job security, enhanced job opportunities, and improved growth prospects. Meanwhile, organizations can take advantage of optimal resource scheduling, greater productivity, and enhanced flexibility in the form of a workforce that is adaptable to different roles [5].

The concept of multi-skilling can be classified into three categories, namely vertical, horizontal, and depth. These categories have varying effects on labour costs, efficiency, quality, and flexibility. Vertical multi-skilling involves gaining knowledge in administrative or supervisory tasks, while horizontal multi-skilling involves learning skills from other areas or functions. Lastly, depth multi-skilling focuses on developing advanced and specialized skills within the same field of work [5].

In general, making decisions about multi-skilled employees involves following a set of rules that determine how much and in what ways multi-skilling should be implemented. These rules can be broken down into three stages: planning, scheduling, and resource assignment. These decisions are interdependent and hierarchical and are made over different periods of time [6].

The MS-RCPSP has numerous real-life applications in various industries. For instance, in software development, MS-RCPSP can help allocate and schedule development tasks across a team of developers who have different skills and availability. Similarly, in manufacturing, it can be used to schedule production tasks across different machines and workers with different skills. In healthcare, it can aid in scheduling medical staff and resources for surgeries and other medical procedures. In construction, it can help schedule a wide range of construction tasks across different workers and equipment. Another application is shutdown, or turnaround, maintenance provided in the recent work of Ertem et al. [7]. Via the use of a realistic case study drawn from a cement plant, the authors highlighted the competitive advantages offered by having flexible or multi-skilled workers which resulted in a reduction in the shutdown time by an average of 16.52%.

While there have been some reviews on the topic of multi-skilling in the workforce, few studies have specifically focused on and quantified its impact on scheduling practises. For instance, [8] conducted a survey on workforce planning that incorporated multiple skills but did not address scheduling issues in particular. In contrast, a relevant work is that of Afshar-Nadjafi [5] who surveyed the broader issue of multi-skilling within scheduling problems. However, to the best of the authors' knowledge, there has not been a focused and a comprehensive review exclusively addressing Multi-Skilled RCPSP. Thus, this study aims to fill this gap via providing a thorough analysis of Multi-Skilled RCPSP while incorporating bibliometric and network analysis techniques. The bibliometric analysis is enhanced by the use of network analysis performed through various computer packages like Gephi and VOSViewer.

The rest of this article is structured as follows: Section 2 summarizes and categorizes the relevant literature pertaining to MS-RCPSP based on several dimensions. Section 3 explains the structured research methodology used and presents some statistical analysis. Section 4 reports the results of the bibliometric analysis, while Section 5 reports the results of the network analysis. Finally, in Section 6, the paper concludes by providing a summary of the main findings and identifying promising areas for future research based on the identified gaps along with useful insights for project managers.

LITERATURE REVIEW

This literature review is divided into four sections, with each focusing on different aspects of the MS-RCPSP. In particular, Section 2.1 discusses various performance measures adopted in the MS-RCPSP and emphasizes the significance of metrics such as completion time, cost, tardiness, and resource utilization in evaluating the quality of a schedule and aligning it with the project objectives. The section highlights the need to jointly consider multiple performance measures in order to captures different aspects of the problem and achieve multi-faceted solutions.

In Section 2.2, various solution approaches for the MS-RCPSP are explored. Exact methods on the likes of Integer Programming and Constraint Programming are discussed, along with techniques such as valid inequalities and Lagrangian relaxation to enhance their performance. Approximate algorithms such as genetic algorithms (GA) and other metaheuristics are also examined. The section provides an overview of these solution methods and their impact on the field.

Section 2.3 stresses on the practicality of MS-RCPSP and delves into its application areas across different industries such as construction, manufacturing, IT/software development, supply chain management, healthcare, oil and gas exploration, nuclear energy and defense. The section discusses the models and algorithms developed to address the challenges characterizing each industry, while highlighting their key features and contributions.

In Section 2.4, the focus shifts to the incorporation of time constraints in the MS-RCPSP. While the primary restriction is the limited availability of resources, the importance of considering time-related factors in project scheduling is acknowledged. The section explores studies that incorporated time constraints, tardiness objectives, and other time-related considerations. It also provides insights into the challenges and strategies associated with managing time constraints in MS-RCPSP.

Performance measures

The MS-RCPSP is known for being a complex problem (NP-hard) and its many variants have been extensively studied in the literature. In essence, towards fulfilling project objectives, the MS-RCPSP requires the scheduling of a series of interdependent tasks in the presence of limited and multi skilled resources, such as labour and equipment. The selection of appropriate performance measures to evaluate the effectiveness of various scheduling strategies is a crucial aspect of this problem. A performance measure is a metric used to evaluate the schedule's quality and determine how well it meets the project's objectives, such as maximum completion time (Makespan or Cmax), cost, tardiness or resource utilization. As per this study, it turns out that the most prevalent performance indicators are project completion time, project cost, and project tardiness. Particularly, 107 papers have utilized project completion time as a performance measure, 68 papers have utilized cost, while 12 papers have utilized project tardiness. In addition, 41 papers have employed alternative measures. It is worth noting, however, that some works have simultaneously considered many performance measures to take into consideration the multi-faceted nature of the problem at hand and come up with

a thorough solution that accounts for trade-offs between different contradictory objectives.
As can be seen in Figure 1, the completion time (Cmax) is a widely utilized performance metric in the context of MS-RCPSP.

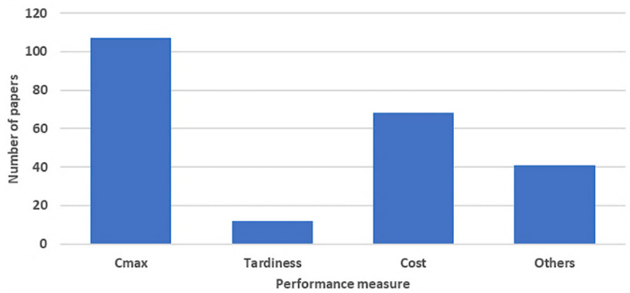


Fig. 1 Measures of performance taken into consideration across the body of articles

Examples include the works of [9, 10, 11] among many others. One of the reasons for its widespread adoption is that it directly relates to the project's deadlines and overall schedule efficiency, often being considered a key performance indicator. In addition, completion time is a quantifiable and objective indicator that may effectively be used to compare various scheduling strategies. The inherent nexus between completion time and other essential performance measures, such as project lateness and cost, is a third reason for the wide usage of completion time as a performance indicator. A project that is finished on time is less likely to incur additional expenses due to delays, as it ensures critical deadline are met.
Cost is another frequently employed performance metric in MS-RCPSP for several reasons. It is indeed inextricably linked to the overall financial performance of the project as well as the project's budget. In many projects, cost is a key indicator of the project's efficiency, and it is frequently used as a benchmark for evaluating the effectiveness of various project scheduling strategies. One can cite for instance the works of [9, 12, 13]. Similar to completion time, another reason for the widespread usage of cost as a performance indicator is that is it a measurable and objective parameter.
The third commonly used performance metric is tardiness. Although it was explicitly considered in only 12 papers ([14, 15] for example), it has a substantial impact on the project's completion time and budget. In essence, tardiness can be measured as the difference between the actual and planned completion durations. The degree to which a schedule adheres to the project's deadlines can be a measure of its efficiency. Tardiness can result in increased costs (e.g. penalties), diminished quality, and missed opportunities. For instance, if a task is delayed, the scheduled resources may not be available for other tasks, resulting in further delays and an implied increase in the costs. When the available resources are less skilled or experienced than those originally scheduled, tardiness can also result in a reduction in quality.
The other performance measures used for the MS-RCPSP are primarily concerned with maximizing staff efficiency [16] and stability [17], as well as schedule stability and robustness [18]. These measures include: matching staff members to activities at their actual skill level [19], best matching human resources to projects [20], minimizing labour instability [17], maximizing the extent of learning throughout the entire project development [21], and maximizing the balance of the employees' workloads [22]. Other measures involve maximizing the achievement of target values aligned with employers' objectives and employees' preferences [23], minimizing reworking risks of the activities [24], minimizing the total number of assignments of workers to projects [25], and minimizing the amount of cross-training [26].
In this study, a total of 110 papers utilized a single performance measure, whereas 59 papers employed a multi-objective function with multiple performance measures (Figure 2). Utilizing a single performance metric can be advantageous as it simplifies the problem and facilitates the comparison of various scheduling options with respect to a specific criterion. However, this also implies that the solution may not be optimal in every respect. For instance, a schedule that reduces tardiness but not resource utilization may not be optimal. In contrast, the use of a multi-objective function with multiple performance measures provides a more holistic approach to the problem and permits a thorough evaluation of scheduling solutions. Furthermore, the obtained solutions would strike a balance that accounts for the inherent trade-offs between objectives. However, this makes the problem more complicated and may necessitate the application of more sophisticated optimization techniques. Various techniques, such as Pareto-optimality, can be utilized to identify a group of non-dominated schedules.

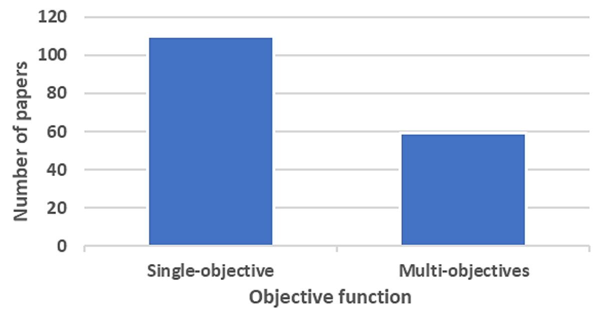


Fig. 2 Number of objective functions taken into account in the pool of papers

The findings of this study indicate that the majority of papers (65 papers) that employ a single objective function used makespan as the sole objective measure (Figure 3) (e.g. [10, 27], etc.).

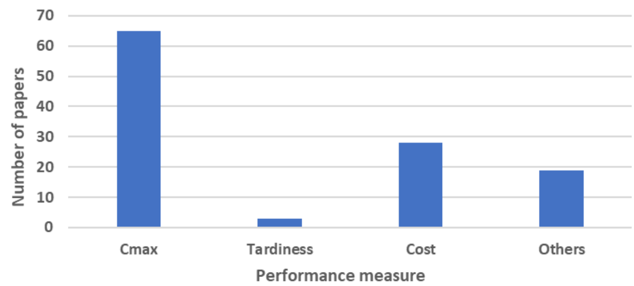


Fig. 3 Performance measures for single objective functions

This is anticipated as the makespan is a proven indicator of the schedule's overall efficiency. Also, 28 papers used only cost as the objective measure ([28, 29] for example), which is a common objective in project scheduling, especially when funds are limited. However, only 3 papers employed tardiness as a single performance measure [30, 31, 32]. Certain types of projects where there are penalties for late completion or where specific deadlines must be met place greater emphasis on tardiness. Additionally, tardiness is closely related to both completion time and cost, as it takes both the duration of the project and any penalties for late completion into account. In many situations, minimizing completion time or cost may also result in a reduction in tardiness. Therefore, it makes sense that researchers place more emphasis on these objectives as opposed to tardiness specifically. Furthermore, tardiness could be used in some situations as a constraint in lieu of a performance measure. The fact that a significant number of papers (59 papers) use multi-objective function indicates that the problem is complex in nature and calls for the consideration of multiple aspects of the schedule in order to find good solutions. As seen in Figure 4, 42 papers utilized Makespan and 40 papers used cost as one of the objective measures.

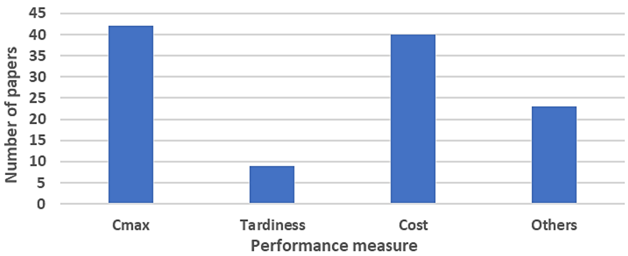


Fig. 4 Performance measures for multi-objective functions

In 9 studies, tardiness served as the objective measure and 23 papers utilized alternative measures. The most frequent combination is completion time and cost (see for example [33, 34]). Indeed, 32 papers considered simultaneously both completion time and cost. This demonstrates the significance of considering both efficiency and budget constraints when addressing the problem of MS-RCPSP.

In conclusion, the MS-RCPSP is a complex and difficult problem that requires careful consideration of multiple performance measures in order to schedule tasks and allocate resources effectively. The most prevalent MS-RCPSP performance indicators are project completion time, project cost, and project tardiness. However, other performance metrics, such as multi-skilled staff assignment and schedule robustness are also essential. Multiple performance measures can provide a more comprehensive view of the scheduling problem and assist in identifying the existing trade-offs between various performance objectives. A single performance measure is easier to solve and compare, but a multi-objective function with multiple performance measures can provide a more comprehensive and balanced solution. In the present review, some objectives, such as total earliness, slack time, risks, quality, were less considered. One possible explanation for this is that these objectives may not be as relevant or significant in certain types of projects or problem situations. For instance, total earliness and slack time are more relevant in projects with early completion incentives. Moreover, some of these objectives may be more challenging to quantify and evaluate. For instance, many variables that can be challenging to measure and analyse might have an impact on the risk of project failure.

Solution approaches

The MS-RCPSP entails the scheduling of tasks and the assignment of multi skilled workers to such tasks with the goal of minimizing project duration while respecting resource limitations. Exact solution methods such as Integer Programming and Constraint Programming utilize mathematical models to determine the optimal schedule. However, due to their computational complexity and the NP-hard nature of the problem, these methods are deemed not efficient for large scale projects involving hundreds or thousands of activities. To enhance the performance of these methods, studies have proposed integrating valid inequalities and Lagrangian relaxation techniques. Alternatively, approximate solution algorithms like GA and metaheuristics, including Variable Neighborhood Search (VNS), have been utilized to obtain near optimal solutions within reasonable CPU time. This section reviews these methods and assesses their impact on the MS-RCPSP field.

Although only a few studies exclusively focused on exact solution techniques, the most commonly used such methods for the MS-RCPSP are mixed-integer linear programming (MILP) and Constraint Programming (CP). These approaches can find the optimal solution within a finite amount of time, but their computational intensity may make them unsuitable for large-scale problems as their CPU time increases exponentially with the problem size. To enhance the performance of MILP approaches, researchers such as [35, 36] have proposed incorporating valid inequalities. Specifically [35], suggested using valid inequalities in a MILP to improve solution speed, while [36] proposed incorporating valid inequalities and reduction tests to further improve the MILP method for single-project, multi-skill staffing and scheduling problems.

In the same context, Montoya et al. [37] presented a combination of Lagrangian relaxation and column generation to minimize the makespan. Li [38] introduced the Hybrid Benders Decomposition (HBD) method for solving the multi-purpose assignment-type RCPSP, which combines mathematical programming, constraint programming, and cut generation strategies to achieve optimal performance. Likewise, Wang et al. [39] proposed an HBD algorithm for solving MS-RCPSP that integrates MILP and CP to improve solution quality and speed. The MS-RCPSP model is divided into two parts, with CP used for project scheduling and MILP for skilled workforce allocation. In another work, Li and Womer [40] investigated the assignment-type MS-RCPSP and proposed a HBD algorithm that combines the advantages of MILP and constraint programming. They also introduced a cut-generating scheme based on temporal analysis in project scheduling to resolve resource conflicts.

In the context of exact solution algorithms, Montoya et al. [41] proposed a branch and price procedure that combined a column generation technique and an activity and timeoriented decomposition scheme, resulting in the discovery of new optimal solutions for previously unknown cases. Bellenguez-Morineau and Néron [42] also presented two exact methods for solving the RCPSP with alternative resource requirements using the branch and bound algorithm. These methods employed a search tree to build partial schedules, either by scheduling one activity per node and adding nodes based on eligible activities' possible execution mode or by scheduling the activity at the earliest feasible start time. In addition, Bellenguez-Morineau and Neron [43] proposed a Branch-and-Bound approach for the MS-RCPSP that avoids explicit resource subset enumeration for activities by using a branching scheme based on reducing slack.

Approximate algorithms are essential for enhancing project scheduling via finding near-optimal solutions, through the implementation of various heuristics and metaheuristics, at a fraction of the time needed by exact approaches. Genetic algorithms (GA) have been used in to address a wide range of project scheduling problems, such as the MS-RCPSP. In IT product development, Chen et al. [44] utilized the Non-dominated Sorting GA II to solve a multi-objective non-linear MILP for the MS-RCPSP. Moreover, GA have been applied by several studies (e.g. [45, 46]) to minimize total resource usage cost or optimize labor resource allocation to activities. A genetic algorithm presented in Zha and Zhang [47] addressed the fuzzy flexible RCPSP. Furthermore, single-criterion or multi-criteria GA based solutions were proposed in [22, 48] for resource allocation in industrial activities planning and scheduling. These studies took into account factors such as multi-skills, working time modulation, and design iteration.

The MS-RCPSP has been solved using different metaheuristics, including the Variable Neighbourhood Search (VNS), path relinking, and cuckoo-search algorithms. One example is the VNS algorithm proposed in [10] which considers resource limitations when scheduling multiple projects in high-end equipment development. This algorithm combines three different neighbourhoods with a scheduling model that takes into account multiple modes and employee skills. Dai et al. [49] introduced a General VNS aimed at minimizing the maximum completion time under step-deterioration, while Dai and Cheng [50] proposed a General VNS based Path Relinking algorithm to tackle the MS-RCPSP with multiple restrictions by incorporating a local refinement process and a path relinking framework. In a related work, the same authors (Dai and Cheng [51] presented a General VNS based Memetic Algorithm that integrated a solution recombination operator and a local optimization procedure.

In the same context, several novel optimization techniques have been proposed by researchers to improve solution quality. For instance, Tian et al. [52] introduced a feedback-based operator to refine the solutions obtained. Hosseinian and Baradaran [53] developed a bi-objective mathematical model that accounts for both deterioration effects and financial constraints, leading to the creation of two new algorithms: the Pareto-based Grey Wolf Optimizer and the Multi-Objective Fibonacci-based Algorithm. In addition, Quoc et al. [54] proposed a new metaheuristic algorithm called DEM, which incorporates a reassignment function. Meanwhile, Chen et al. [21] presented a multi-objective optimization model that aims to enhance staff skills, reduce development cycle time, and improve product quality. They utilized an improved multi-objective Pareto ant colony optimization algorithm to solve the problem. Chen et al. [55] introduced a multi-priority rule approach in their 2019 paper. Similarly, Maghsoudlou et al. [56] presented an ant colony-based metaheuristic algorithm, while Ren et al. [57] developed an integrated nested optimization algorithm. Ma et al. [58] conducted a study on the proactive project scheduling problem and made use of a two-layer nested tabu search heuristic algorithm in their analysis.

In addition to these efforts, several optimization techniques have been proposed to tackle project scheduling problems that involve uncertainty in project estimation. For instance, one such technique is the Multi-Objective Imperialist Competitive Algorithm [34], which aims to minimize both project duration and labour cost. Additionally, two stochastic optimization approaches have been proposed in Felberbauer et al. [59]. Chen et al. [60] also introduced an approach to solve a flexible RCPSP with competency differences, using dynamic programming. This method incorporates a parameter and an estimation formula to measure staff competency and formulates the problem as a set of single-objective optimization problems for optimal duration and cost, while taking into account their bi-objective importance. An initial network diagram of multiple projects was established, and a feasible solution set that satisfies constraint conditions was obtained using an enumeration algorithm.

Several other metaheuristics have been proposed for addressing various project scheduling challenges. Polo Mejia et al. [61] introduced a greedy algorithm that utilizes priority rules, while Liu et al. [62] proposed a two-dimensional particle swarm algorithm. Additionally, Maghsoudlou et al. [24] proposed three cuckoo-search based multi-objective approaches, while Dai at al. [50] put forward a tabu search algorithm that incorporates four neighbourhood structures and two mutation operators. In contrast, Dolgui et al. [63] presented traditional and randomized heuristics for solving the production scheduling problem, and Maghsoudlou et al. [64] suggested using a multi-objective invasive weed optimization algorithm.

Numerous studies have focused on addressing the MS-RCPSP by using Teaching-Learning-Based Optimization (TLBO) algorithms. For example, Joshi et al. [65] presented a mathematical model that uses a Weighted Sum TLBO algorithm to minimize the Makespan and skill divergence span. Cai et al. [14] extended the Multi-Mode MS-RCPSP and proposed a multi-objective invasive weed optimization algorithm. This algorithm includes a new solution representation scheme, initialization method, local search procedure, and self-adaptive penalty-based constraint handling method. Zhu et al. [66] proposed a discrete oppositional multi-verse optimization algorithm that improves solution quality and efficiency. This algorithm uses various techniques such as black/white holes phase, improved path relinking methods, opposition-based learning method, and repair-based decoding scheme. Zabihi et al. [67] developed two hybrid multi-objective TLBO algorithms based on learning effects to find near-optimal solutions for the multi-objective multi-skilled resource-constrained project scheduling problem. Wang and Zheng [11] suggested a knowledge-guided multi-objective fruit fly optimization algorithm that aims to decrease makespan and total cost. Shen et al. [18] introduced the Multi-Objective Two-Archive Memetic Algorithm, which is designed to handle the dynamic nature of software project environments and varying levels of employee motivation and learning ability. Finally, Zheng et al. [68] recommended using a TLBO algorithm to minimize the Makespan in the MS-RCPSP.

The complexity of project scheduling can pose significant challenges, particularly when multiple constraints are involved. To address these difficulties, hybrid algorithms have been developed. These algorithms incorporate both heuristics, which are techniques for solving problems derived from practical experience, and meta-heuristics, which are general problem-solving strategies. The aim of these hybrid algorithms is to provide superior results in project scheduling by combining the strengths of both heuristics and meta-heuristics. A number of studies have been conducted to address the MS-PSP through combining GA with other metaheuristics. For example, [28] proposed a framework for organizations that employ a multi-skilled workforce and utilize energy tariffs dependent on the time-of-use to implement their projects. To handle large-scale instances, two intelligent meta-heuristics, namely electromagnetic like algorithm and GA, are used. Another study introduced a Multi-Objective Genetic Programming Hyper-Heuristic approach to minimize both the makespan and total cost, taking into consideration factors such as task processing time, robot transfer time, skill depth, and breadth [9]. Additionally, a genetic programming hyper-heuristic algorithm was proposed to solve MS-RCPSP in [69] by utilizing a single task sequence vector for encoding solutions, a repair-based decoding scheme, and genetic programming as the high-level strategy. Ren et al. [70] developed a hybrid algorithm that combined a two-level decision scheme and a local search optimization scheme to minimize the Makespan of projects with hierarchical skill levels. The GA was used to determine the activity priority list, while a key resource decision heuristic algorithm was employed to generate a feasible solution. Javanmard et al. [71] proposed genetic and particle-swarm-based algorithms to handle large scale real-life problems. Maghsoudlou et al. [64] introduced a Hybrid GA to handle both project scheduling and staff allocation, with the goal of minimizing the total project cost, utilizing a priority rule-based parallel schedule generation scheme. Another study used Adaptive Pareto Sampling with Nondominated Sorting GA II to solve a bi-objective stochastic optimization problem [72]. Furthermore, Campos et al. [35] proposed the use of both GA and Ant Colony Optimization algorithms to find the optimal solution for the open shop scheduling problem.

Several studies have proposed solutions to the Multi-Project Scheduling Problem, including a two-phase solution that employs Statistical Process Control in [73], and a new variant of the problem called the MS-PSP with partial preemption in [74]. To solve this variant, various heuristic algorithms were proposed, such as a serial greedy algorithm and a binary-tree-based search algorithm. In addition, Javanmard et al. [75] and Myszkowski et al. [76] proposed intelligent algorithms optimized with the Taguchi method and Evolutionary Algorithm, respectively, to address scheduling problems with multi-skilled workforces. Furthermore, Shahnazari-Shahrezaei et al. [77] proposed two meta-heuristic algorithms based on Differential Evolution and Particle Swarm Optimization to solve the MS-RCPSP. Meanwhile [78], explored the effectiveness of different selection operators in the Non-dominated Sorting GA II for the bi-objective MS-RCPSP and found that a hybrid approach using Differential Evolution and Greedy Algorithm yielded promising results.

In conclusion, the MS-RCPSP has been tackled through a variety of methods that seek to find the optimal solution or a near-optimal solution. Exact solutions have been proposed using Integer Programming and Constraint Programming, but they may not be suitable for large-scale problems. To further improve the performance of these methods, valid inequalities and reduction tests have been proposed. Other approaches, such as Lagrangian relaxation, Hybrid Benders Decomposition, and Branch and Price procedures, have been introduced to find optimal solutions. Approximate algorithms, including GA, have also been used to find near-optimal solutions. The MS-RCPSP has also been tackled through different metaheuristics, including VNS, path relinking, and cuckoo-search algorithms. These approaches have shown great potential in improving project scheduling by finding optimal solutions or near-optimal solutions through the use of various heuristics and metaheuristics. The choice of a specific approach depends on the problem's scale, complexity, and constraints, and it is essential to consider the strengths and weaknesses of each method when selecting the most-suited solution approach.

Application areas

A wide spectrum of industries often encounter project scheduling difficulties coupled with constraints on the availability of resources. In this section, we highlight the practical relevance of the MS-RCPSP and delve into how this problem has been applied across several industries to solve project scheduling challenges caused by resource limitations. Examples of such applications include construction [79, 80], manufacturing [81, 82], IT/software development [79, 83], supply chain management [49] healthcare [72, 84], oil and gas exploration [33], energy and nuclear power [28, 74], and defense [85, 86].

In the construction industry, which is grappling with resource limitations, several models and algorithms have been developed to address this challenge. Examples of such models include the stochastic multi-skilled resource scheduling model and the cost-resource replacement trade-off algorithm. The stochastic multi-skilled resource scheduling model, as discussed in Isah and Kim [79], combines a schedule risk analysis model with an existing multi-skilled resource scheduling algorithm to create a feasible and realistic schedule. Similarly, Wongwai and Malaikrisanachalee [29] proposed a cost-resource replacement trade-off algorithm that focuses on scheduling multi-skilled resources in construction projects.

Furthermore, several studies have explored the use of multi-skilling and cross-training of construction resources in offsite construction, such as [80, 87]. These studies employed optimization and multi-criteria decision-making techniques to compare the performance of different labour skill sets, while others focused on process integration and cross-training to identify optimal process integration architectures. Other studies, such as [88] and [89], proposed models and algorithms for scheduling multi-skilled human resources in the construction industry.

In the IT/software development sector, various models and frameworks have been developed to evaluate the risks and uncertainties associated with resource-constrained project schedules, resource evaluation, decision-making on tender estimations, and human resource allocation. For example, one model presented in Isah and Kim [79] accomplished two objectives namely assessing the risks and uncertainties associated with resource-constrained project schedules and establishing practical schedules. Chiang and Lin [83] introduced a framework for resource evaluation, decision-making on tender estimations, and human resource allocation for projects with fixed durations. Chen et al. [21] proposed a multi-objective optimization model for managing a project portfolio and assigning multi-skilled personnel. Additionally, Korytkowski and Malachowski [90] suggested a methodology for estimating activity duration based on the hierarchical skill model and learning curves. In Celkevicius and Russo [91], an integrated model for human resource allocation and levelling in IT projects was presented based on a case study of 14 projects in an IT outsourcing company. In addition to project scheduling, research also focused on software project scheduling. For instance, Guo et al. [92] and Shen et al. [18] proposed models that considered employee learning and forgetting characteristics, motivation, learning ability, and skill difficulty. Chen et al. [44] introduced a multi-objective non-linear mixed integer programming model for scheduling complex software projects in IT product development. Finally, Li et al. [93] proposed a constraint programming approach to address the complex problem of MS-RCPSP in software companies.

Effective management of a multi-skilled workforce is critical for achieving maximum productivity and timely project completion in the manufacturing industry. To prevent downtime and improve overall project efficiency, employees with various skills and abilities must be managed to perform multiple tasks. Resource constraints are common in manufacturing industries, necessitating careful planning of project scheduling to allocate limited resources such as time, equipment, and personnel effectively. To address the challenges associated with multi-mode and multi-skill RCPSP, several studies have highlighted the importance of effective scheduling algorithms and models ([14, 81] for example). Bi-objective optimization models are particularly useful in manufacturing to reconcile conflicting objectives of production cost and time constraints [94]. Additionally, the discrete equipment manufacturing workshop scheduling problem poses unique challenges that require optimizing the utilization of production resources, necessitating proper scheduling of resources to ensure maximum efficiency [55]. Flexible resource investment and the MS-PSP with partial pre-emption are other challenges that require careful planning, with various models and algorithms developed to address them effectively (e.g., [57, 95]). Finally, synchronization of operations is necessary to maintain production flow in paced assembly lines, requiring careful scheduling and coordination of operations [63].

It is noted that staff scheduling is a crucial aspect of workforce management, as it involves allocating resources to specific tasks and roles based on available skills, experience, and workloads. Effective project management involves several critical tasks, including resource allocation, task scheduling, and staff assignment. The MS-RCPSP has been a topic of considerable interest in recent years, with several studies addressing this problem. These studies have proposed various models and algorithms that leverage optimization and learning techniques to automate and optimize the scheduling process.

Several studies have addressed the MS-RCPSP, where activities with skill requirements are scheduled and multi-skilled resources are assigned to those activities. Some of these studies have also introduced new dimensions to measure the skills of multi-skilled resources [96, 97]. Another study developed an integrated multi-project scheduling and multi-skill human resource assignment model for R&D projects under uncertainty, taking into account the learning effect to reduce costs and increase project efficiency [98]. One such study proposed a four-stage model that includes a weighted compatibility indicator to measure auditor competency and multi-choice goal programming to find trade-offs between project efficiency and competency improvement for internal audit managers [97]. Optimization models have also been proposed to optimize the allocation of limited resources to project activities considering uncertainty conditions for parameters and workers' different skill proficiencies [99, 100], and to minimize external costs when internal resources are not sufficient [59]. The integrated problem of project scheduling and personnel staffing has also been explored, aiming to minimize staffing cost while scheduling project activities and composing a staffing plan simultaneously [101]. Other studies proposed MILP models for staffing problems faced by firms with concurrent projects or for multi-mode multi-project human resource constrained scheduling problems [102, 103]. Finally, Fernandez-Viagas and Framinan [104] addressed the decision problem of scheduling tasks in a project and assigning staff to those tasks, where tasks require specific skills and their length depends on the number of employees assigned, focusing on service companies where tasks scheduling and staff assignment are interdependent.

To summarize, effective management of multi-skilled workforces is crucial for achieving maximum productivity and timely project completion in various industries. Different industries have developed models and algorithms to manage their workforce. The construction industry, in particular, has seen the development of various models and algorithms such as the stochastic multi-skilled resource scheduling model and the cost-resource replacement trade-off algorithm. In the IT/software development industry, various models and frameworks have been developed to evaluate risks and uncertainties, resource evaluation, decision-making on tender estimations, and human resource allocation. In the manufacturing industry, effective scheduling algorithms and models are essential to reconcile conflicting objectives of production cost and time constraints. Various challenges require careful planning, and various models and algorithms have been devised to address them effectively.

Time constraints in MS-RCPSP

While our primary objective for this review is to examine the MS-RCPSP in the context of resource constraints, numerous studies have also investigated additional constraints, including time constraints, tardiness objectives, and other time-related considerations. In this section, we will explore papers addressing the MS-RCPSP while also accounting for time related aspects into their analysis.

In addition to resources constraints, time constraints were considered in many papers. For example, Dai and Cheng [50] proposed a general variable neighbourhood search-based path relinking algorithm (GVNS-PR) to solve the MS-RCPSP with multiple restrictions, including time constraints. The algorithm integrates local refinement and path relinking framework to achieve highly competitive results on two datasets, including benchmark instances from the literature and a revised dataset with researched restrictions. Similarly, Geibinger et al. [105] addressed a real-world scheduling problem related to the RCPSP in industrial test laboratories while respecting deadlines and other constraints. They presented different constraint programming models and search strategies, evaluating their approaches using CP solvers and a MIP solver on a set of generated instances of different sizes. Their best approach finds feasible and optimal solutions for instances generated based on real-world test laboratory problems. Tackenberg and Duckwitz [106] proposed an extension of the RCPSP to apply it to maintenance problems of high frequency infrastructure where the infrastructure is only temporarily available for maintenance and repair work during the workforce shift. They presented a multi-criteria evolutionary algorithm with a novel problem representation for developing shift plans that maximize the utilization rate of technicians while minimizing waiting times caused by other actors' use of the infrastructure. The results of the implemented algorithm indicate rapid convergence towards optimal teamwork allocation and task sequencing. Liu et al. [62] also addressed pre-emptive project scheduling with time-window constraints on multi-skilled resources using an integer programming model and branch and bound method. They proposed two pruning rules and node priority rules to reduce the number of branch nodes, and a greedy algorithm is employed to verify resource constraints. The effectiveness of dominance strategies is demonstrated through experiments using the improved PSPLIB (Project Scheduling Problem Library), and the proposed method is shown to be more efficient and effective than Cplex and basic heuristic algorithms. The work of Arashpour et al.[107] focused on optimizing off-site construction production by defining the optimal product sequencing with time constraints, which minimizes changeover time between product classes. Modeling the problem with optimization-based metaheuristics, the paper aims to maximize production output. The models and conclusions presented in this work are applicable to off-site manufacturers of building components. Finally, time constraints were considered for electricity tariff time dependency. Indeed, Najafzad et al. [94] presented a bi-objective optimization model for multi-skill project scheduling problems that takes shift differential payments and time-of-use electricity tariffs into consideration to minimize project total cost and completion time. The proposed model is solved using multi-objective decision-making techniques. Taking into account time-of-use electricity tariffs and regular/overtime payments reduces not only energy costs and total project costs but also benefits power distribution networks.

Tardiness has been considered a time constraint in several papers. Santos and Tereso [108] extended the RCPSP to include multi-level (or multi-mode) activities that require different resource levels in a software application. Their objective was to minimize project cost and penalties for tardiness while also receiving a bonus for early delivery. The processing time of an activity is determined by the longest duration resulting from a particular resource allocation. Similarly, Liu et al. [62] proposed an optimization model for design streamlining scheduling problems in development projects. This model considered multiple executive modes, multi-skilled employees, and precedence to minimize the project's duration and tardiness. They used a two-dimensional particle swarm algorithm to find the optimal solution and presented a case study to demonstrate the effectiveness of the proposed model and algorithm. Finally, [24] addressed a pre-emptive multi-skilled resource-constrained project scheduling issue with hard/soft interval due dates in a just-in-time setting. Their goal was to minimize the total cost of allocating personnel to skills, penalties for tardiness, and pre-emption fees. They suggested two integer programming formulations and created an ant colony-based metaheuristic to address the model's real world problems of large scale.

Many studies have addressed staffing scheduling problems with time considerations. Karam et al. [109] developed a MILP model for a flexible working hours integrated project scheduling and multi-skilled workforce allocation problem. The model considers the assignment of scarce workers with varying skill levels and efficiencies to tasks with variable skill requirements and durations.

Additionally, the model incorporates flexible working hours and effective team building to develop workers' skills through knowledge transfer. Shen et al. [18] proposed a Q-learning-based memetic algorithm for multi-objective dynamic software project scheduling, which considers human factors such as motivation and learning ability, skill proficiency, and employee satisfaction in addition to traditional objectives like project duration, cost, robustness, and stability under practical constraints. Their algorithm learns the most appropriate global and local search methods for different software project environment states by using Q-learning. The algorithm is effective in improving convergence performance in dynamic environments, while maintaining a good distribution and spread of solutions. Maenhout and Vanhoucke [101] analysed the integrated project scheduling and personnel staffing problem for different personnel resource types. They evaluated different scheduling policies and practices and examined the impact of introducing more flexible resource types, such as overtime and temporary help. The results showed that non-cyclic scheduling leads to a lower staffing cost as compared to cyclic scheduling, and flexible temporary resources are essential to respond to demand variability. Li and Womer [40] proposed a hybrid Benders decomposition algorithm that combines mixed-integer linear programming (MILP) and constraint programming (CP) to solve a RCPSP where the resources are multi-skilled personnel. The objective is to minimize total staffing costs. A cut-generating scheme based on temporal analysis is introduced to resolve resource conflicts. The algorithm is tested and found to be more effective and efficient than using MILP or CP alone. The study concludes that the hybrid algorithm can be applied to solve large and complex scheduling problems. Fauske [85] proposed a GA for solving the troops-to-tasks problem in military operational planning. The study was motivated by a request from Norwegian military staff who acknowledged the potential for solving the troops-to-tasks analysis more effectively by using optimization techniques. The troops-to-tasks problem generalizes the well-known resource-constrained project scheduling problem, and the developed algorithm attains feasible solutions within reasonable computational time for all instances tested. Attia et al. [48] provided a methodology for the allocation of flexible human resources in industrial activities planning and scheduling. The paper takes into account two levers of flexibility, one related to the working time modulation, and the other to the varieties of tasks that can be performed by a given resource (multi-skilled actor). The model helps to guide various allocation choices and appreciate the impact of these choices on task durations.

Time constraints were also taken into account in load balancing scheduling problems. In two related works, Ren and Lu [12, 110] proposed solutions to two different project scheduling problems. In the first paper, they developed an algorithm to solve the flexible resource workload balancing and investment project scheduling problem (FRWBIP), which is an extension of the resource investment project scheduling problem. The objective is to minimize the weighted resource availability cost and workload balancing penalty. They use a heuristic algorithm to obtain the upper and lower bounds of resource requirements, and a GA to solve FRWBIP. In the second paper, they extended the multi-skill resource investment problem to consider workload balancing of resources. The objective of the mathematical model is to minimize the weighted resource usage cost and resource balancing penalty, and they propose a GA to solve the problem. Celkevicius and Russo [91] proposed an integrated model for simultaneous resource allocation and workload levelling of human resources in IT projects based on a single case study conducted in a large company of IT outsourcing services. The proposed model suggests using the critical path technique and making managerial decisions based on information of availability, key skills, holidays, and days off for human resources.

In conclusion, the MS-RCPSP and the MS-TCPSP are two project scheduling problems that differ in the constraints they consider. While the MS-RCPSP considers resource constraints such as labour, equipment, and material availability, the MS-TCPSP considers time constraints such as task duration and deadlines. However, many studies have combined both constraints and have addressed the MS-RCPSP with time related constraints. Tardiness is a common time constraint considered in many studies, and staffing scheduling problems have also been addressed with time considerations. These studies have proposed various algorithms, models, and metaheuristics to solve these problems, considering realistic size cases and different objectives. Overall, these studies provide valuable insights for project managers to effectively schedule tasks while optimizing resources, minimizing completion time, and ensuring task completion within their deadlines.

RESEARCH METHODOLOGY AND DATA STATISTICS

In order to thoroughly investigate the existing body of knowledge pertaining to the scheduling of multi-skill resources throughout the course of a project, this work employs a systematic literature network analysis, an integrated approach that combines systematic literature review, bibliometric analysis, and network analysis. According to Saunders et al. [111] bibliometric analysis assesses academic productivity, identifies research tendencies, hence offering the ability to detect, organize, analyze, and quantify publications in a specific research domain. Comprehensive network analysis, including citation and co-citation analysis, was utilized to discover emergent study fields by identifying research clusters and key contributing scholars within each cluster. A systematic literature review adopts a well-defined and structured approach to search for, identify and select relevant articles based on their content, ultimately unveiling existing research gaps and directing future research efforts into such unexplored areas.

The bibliometric analysis methodology adopted in this paper was developed by Saunders et al. [111] and later used by Fahimnia et al. [112] and Mishra et al. [113] among many others. Scopus database was solely used to collect all the relevant articles used in this paper, as Scopus is known for being one of the largest multi-disciplinary abstract and citation database of peer-reviewed works. Moreover, Scopus is an indexed and organized database that provides essential publication details with practical metadata export features [114, 115].

Defining the appropriate keywords

Identifying the most appropriate search terms/keywords to adequately capture relevant publications pertaining to the intended topic is the first and the most critical step in the data collection process. According to Saunders et al. [111], a structured literature review necessitates an iterative process of defining and refining relevant search keywords, literature search, and analysis. In principle, the keywords used shall be neither too generic resulting in a large number of irrelevant articles nor too specific in a way that closely related articles are overlooked or remain uncaptured. To that end, different combinations of search queries involving the keywords: "multi", "skill", "skilled", "resource", "constrained", "project", "scheduling", "flexible resources" and "problem" were used to uncover a wide range of project scheduling problems while linking them with the AND conjunction. Following multiple iterations of refining search terms, the five strings shown in Table 1 were adopted to search Scopus database within papers' titles, abstracts, and keywords fields and using the "advanced document search" option. The two keywords "resource" and "constrained" were deliberately dropped out of the last three search strings to account for other types of projects beyond those characterized by limited availability of resources. Furthermore, the last search query adopts the keywords "flexible resources" as it was noted during early stages of the search process that several works utilize these keywords to indicate the existence of resources that are capable of performing several tasks requiring various skill levels.

Table 1
Search queries and number of articles retrieved

Search query	No. of articles retrieved
multi AND skill AND resource AND constrained AND project AND scheduling AND problem	76
multi AND skilled AND resource AND constrained AND project AND scheduling AND problem	37
multi AND skill AND project AND scheduling AND problem	129
multi AND skilled AND project AND scheduling AND problem	78
project AND scheduling AND problem AND "flexible resources"	41
Total	**361**

Initial search results

The applied search queries shown in Table 1 were restricted to articles published between the years 2000 and 2021 initially resulting in a total number of 361 scholarly articles, including journal papers, conference proceedings, extended abstracts as well as book chapters. To further process the data, all information pertaining to the returned articles obtained from Scopus were exported to a CSV file, including the title, abstract, author(s), authors' keywords, affiliation, source title, etc. The returned Scopus articles were then subjected to a multi-stage systematic filtering process, in which one-page extended abstracts were excluded along with duplicates which are articles satisfying more than one search query and appearing more than once. Afterwards, the title and abstract of the remaining articles were closely examined to assess their relevance to the scope of the review, retaining only relevant articles. Subsequently, the remaining articles' contents were thoroughly examined to ensure that the retained articles were pertinent to the review scope. Lastly, the content and the references of the resulting articles were screened where relevant articles not captured via the multiple search queries were added towards the attainment of a more comprehensive database. As a result of this multi-stage refinement process, the pool of articles was reduced down to 171 closely related papers.

Initial data statistics

Figure 5 depicts the annual distribution of the relevant publications from the year 2000 until the end of 2021. As shown in the figure, there were only few publications prior to 2010 with several years having either 1 or no publications at al. Nevertheless, the number of publications exhibited an overall increasing trend from 2010 onwards with 30 publications in 2019 only.

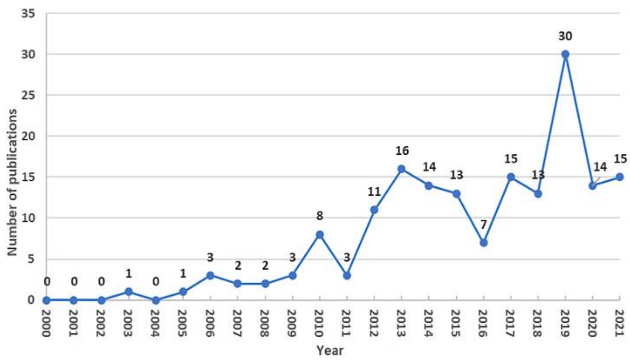


Fig. 4 Annual breakdown of the relevant research articles

This noticeable increase in the number of publications over time, despite some fluctuations, reflects the trendiness of the subject at hand and its growing popularity among researchers. Table 2 displays the top 14 contributing journals as measured by the number of publications, where European Journal of Operational Research (EJOR) was the leading contributor, publishing seven articles, which clearly revels the applicability of Operation Research (OR) tools to handle various modelling and solution aspects of MSPSP.

Table 2
Top contributing journals based on publications

Journal	No. of articles
European Journal of Operational Research (EJOR)	7
Automation in Construction (AC)	6
Lecture Notes in Computer Science Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics (LNCS)	6
Computers and Industrial Engineering (CIE)	5
International Journal of Production Research (IJPR)	4
Journal of Scheduling (JS)	4
Applied Soft Computing Journal (ASCJ)	3
Expert Systems with Applications (ESA)	3
Information Sciences (IS)	3
International Journal of Advanced Manufacturing Technology (IJAMT)	3
Computer Integrated Manufacturing Systems (CIMS)	3
Control and Decision (CD)	3
RAIRO Operations Research (RAIRO-OR)	3
Soft Computing (SC)	3
Total	**56**

In addition, Table 3 provides a more detailed breakdown of the top 6 contributing journals' annual publications over a 10-years' time window starting from the year 2012. It can be noted that there are no new journals that appeared in Table 3 as compared to Table 2. Another observation is the dominance of journals having a wider scope beyond those focusing merely on project management related topics.

Table 3
Top publishing journals since the year 2012

Journal	Publication Year										
	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	Total
AC	1			1	1		2				**5**
CIE			1					1	1	2	**5**
LNCS			1		1	1		1			**4**
EJOR							1	1		1	**3**
IJPR					1	1			1		**3**
IJAMT	1	2									**3**
Total	**2**	**2**	**2**	**1**	**3**	**2**	**3**	**3**	**2**	**3**	**23**

BIBLIOMETRIC ANALYSIS

An emerging tool that has been gaining momentum among researchers is bibliometric analysis which represents a powerful tool towards screening, organizing, analyzing, and categorizing publications related to a particular field of study. It essentially seeks to assess academic productivity, identify research tendencies and detect the impact of various thematic clusters within the field [115, 116]. One can get a sense of the most influential authors along with their affiliation and the most important relevant keywords, which would lead future researchers to the emerging research subtopics. In principle, there exist several software packages that are deemed useful to conduct bibliometric analysis such as BibExcel [117]. In this work, we adopt the latter due to its compatibility with a wide range of network analysis software, such as Gephi and VOSViewer, as well as its proven flexibility in handling metadata imported from Scopus database. A more elaborate discussion on the advantages of BibExcel software can be found in the work of Persson et al. [117]. To proceed with the analysis, the first step comprises transforming the pool of documents generated by Scopus, along with all bibliometric information, into a RIS (Research Information Systems) format. Afterwards, BibExcel software is utilized to convert the RIS file to other file formats allowing for the extraction of needed information for the bibliometric analysis as detailed next.

Author influence

Extracting the authors' field from the metadata reveals the top contributing authors to the research topic at hand. Table 4 shows the top eleven contributing authors as measured by their respective number of published articles.

Table 4
Top contributing authors

Author	No. of papers
Myszkowski, P.B.	12
Afshar-Nadjafi, B.	8
Correia, I.	7
Laszczyk, M.	7
Bellenguez-Morineau, O.	5
Arashpour, M.	5
Baradaran, V.	5
Hosseinian, A.H.	5
Maghsoudlou, H.	5
Shahnazari-Shahrezaei, P.	5
Lu, Z.	4

It turns out that Myszkowski, P.B., has published 12 articles, making him the most prolific author in this field. In shall be noted that many of Myszkowski's published works dealt with the optimization and scheduling of MS-RCPSP, in specific. As shown in Table 4, the second most prolific contributor is Afshar-Najafi, B., with 8 publications, followed by Correia, I. and Laszczyk, M., with seven publications each.

Keyword statistics

To gain further insights, the most frequently occurring words and phrases from the title and authors' keyword sections were extracted. Table 5 displays the most frequently used keywords by the authors of the selected 171 papers, while the most prevalent keywords in the titles of those papers are displayed in Table 6. The relevance of such information is that it may indicate how the used search stings above can be amended via the inclusion of additional keywords to capture more articles. As per Table 5, the keyword "scheduling" in general, followed by the more specific term "project scheduling" and the very specific terms "resource-constrained project scheduling problem" are the most frequently used by authors. As can be noted, many of the authors resort to the use of optimization techniques, whether exact approaches or metaheuristics to optimize the related decisions, as reflected by the terms "optimization", "integer programming" and "genetic algorithms". One may note the commonality among many of the most appearing keywords seen in Tables 5 and 6. An interesting observation is the emergence of the word "resource" as a stand-alone or as part of longer phrases "e.g. resource-constrained" which indicates that the existence of flexible resources possessing multiple skills has been considered to a larger extent in the context of "resource constrained" as compared to "time constrained" project scheduling problems. It is also worth noting that the majority of the common keywords appearing in Tables 5 and 6 are similar to those used to select the final pool of papers.

Table 5
Top author keywords

Keyword	Frequency
Scheduling	154
Project scheduling	112
Resource-constrained project scheduling problem	47
Optimization	46
Project scheduling problem	40
Genetic algorithms	36
Integer programming	33
Multi-skilled resources	31
Multi skills	29
Problem solving	23

Table 6
Top title keywords

Title word	Frequency
Scheduling	155
Project	128
Problem	93
Multi-Skill	53
Multi-Skilled	47
Algorithm	43
Resource	43
Resource-constrained	34
Optimization	27
Multi-Objective	25

NETWORK ANALYSIS

Conducting a network analysis requires specialized software, and there are several options available such as Pajek, HistCite, VOSViewer [118] and Gephi [119]. However, some of these software suffer from certain limitations. For instance, Pajek only works with "Net" files, and HistCite is designed for Web-of-Science output files [112]. This study employs Gephi and VOSViewer to create visualizations of bibliographic data. Gephi is a powerful tool that enables flexible visualizations of complex data which is attributed to its various built-in toolboxes for network analysis. However, Gephi is not compatible with Scopus's RIS file format directly and requires instead a network file from BibExcel. On the other hand, VOSViewer is a simpler tool that can read Scopus's RIS file, eliminating the preprocessing step. While VOSViewer has more limited capabilities in dealing with bibliographic data than Gephi, it is useful for simple network analysis tasks. This work covers several network analysis techniques, including citation analysis, PageRank analysis, co-authorship and co-word analysis, co-citation analysis, and data clustering. Detailed explanations of each technique are provided in the following subsections.

Citation analysis

Citation analysis calls for evaluating and ranking relevant papers based on citation frequency, which helps unveil significant papers in a research field [120]. In addition, the paper ranking indicates the researcher's impact on that specific field of research [121, 122]. It is important to note that other methods that will be later discussed can also assess the impact of a paper in a research area. Based on local and global citations, Table 7 displays the most influential papers addressing MS-RCPSPs. Local citation denotes the number of times a paper is cited by other papers in the selected paper pool, while global citation refers to the number of times a paper has been cited by other papers in different areas of research. The large difference between local and global citations indicates that the articles received noticeable attention from researchers in other fields. According to Table 7, Ren et al. [12] is the most cited paper locally, with 8 local citations. However, Li and Womer [40] is the most cited paper globally, with 121 global citations.

Table 7
Top articles based on citation analysis

(Author, year)	Ref.	Global Citations	Local Citations
(Ren et al., 2017)	[12]	8	8
(Li and Womer, 2009)	[40]	121	6
(Myszkowski et al., 2013)	[123]	28	6
(Myszkowski, Skowroński, Olech, et al., 2015)	[124]	75	5
(Montoya et al., 2014)	[41]	34	5
(Bellenguez and Néron, 2005)	[125]	72	4
(Bellenguez-Morineau and Néron, 2007)	[126]	82	4
(Firat and Hurkens, 2012)	[127]	82	4
(Bellenguez-Morineau, 2008)	[128]	38	4
(Myszkowski, Skowroński, and Sikora, 2015)	[129]	22	4
(Correia and Saldanha-Da-Gama, 2014)	[130]	29	4

PageRank analysis

The most common approach used for assessing the importance of publications is citation analysis [131]. The importance of a publication can also be assessed through the number of times it has been cited in highly cited papers [132]. Brin and Page [133] introduced this method, which is referred to as "PageRank analysis" which considers both prestige and popularity and ensures they both are correlated in the analysis.

In a network of N papers, the PageRank of paper A is calculated by:

$$PR(A) = \frac{(1-d)}{N} + d\left(\frac{PR(T_1)}{C(T_1)} + \ldots + \frac{PR(T_n)}{C(T_n)}\right), \quad (1)$$

where:

$T_1,\ldots, T_n$ represent papers that cited paper A,

parameter d defines the damping factor and has a value between 0 and 1.

The damping factor describes the random walk's fraction that propagates along citations [112]. Moreover, it represents the number of times the paper cited other papers.

It is important to note that in the case of $C(T_i) = 0$, the $PR(T_i)$ will be divided by the papers' number instead of $C(T_i)$. In addition, in citation networks, the damping factor generally assumes a value of 0.5 [134]. However, other scholars, like Brin and Page [133], suggested different values, such as 0.85.

The top 10 papers based on PageRank were identified using Gephi, as shown in Table 8. It is important to note that before finding the PageRank, the self-loops were removed so that the PageRank of the papers added up to one. Upon comparing Tables 7 and 8, it can be noted that only 3 papers appear in both tables, which are [12, 41, 127]. Note that [40] appears to be one of the most important papers as it has the highest PageRank score and it also ranks first in terms of global citations. Given that citation scores are built gradually over time, there is a lower chance of citing recent papers by highly cited papers.

Table 8
Top articles based on PageRank

(Author, year)	Ref.	Page Rank	Global Citations	Local Citations
(Li and Womer, 2009)	[40]	0.029676	121	6
(Ren et al., 2017)	[12]	0.024031	8	8
(Firat and Hurkens, 2012)	[127]	0.022476	82	4
(Tabrizi et al., 2014)	[135]	0.019819	10	2
(Montoya et al., 2014)	[41]	0.018274	34	5
(Gutjahr and Reiter, 2010)	[72]	0.017925	38	3
(Tiwari et al., 2009)	[136]	0.015261	57	2
(Smet et al., 2014)	[137]	0.012736	39	1
(Wongwai and Malaikrisanachalee, 2011)	[138]	0.012241	39	1
(Walter and Zimmermann, 2016)	[102]	0.011779	22	2
(Yannibelli and Amandi, 2013)	[20]	0.011747	21	2

Co-authorship analysis

There was a total of 356 authors who contributed to the 171 papers. As shown in Figure 6, the VOSViewer software was utilized to visualize the co-authorship pattern. The network visualization employs nodes to represent authors and edges to connect nodes that co-authored the same paper. Moreover, the size of a node is proportional to the number of edges connecting it to other authors. As shown in Figure 6, the network authors created 21 colored clusters based on the publication year.

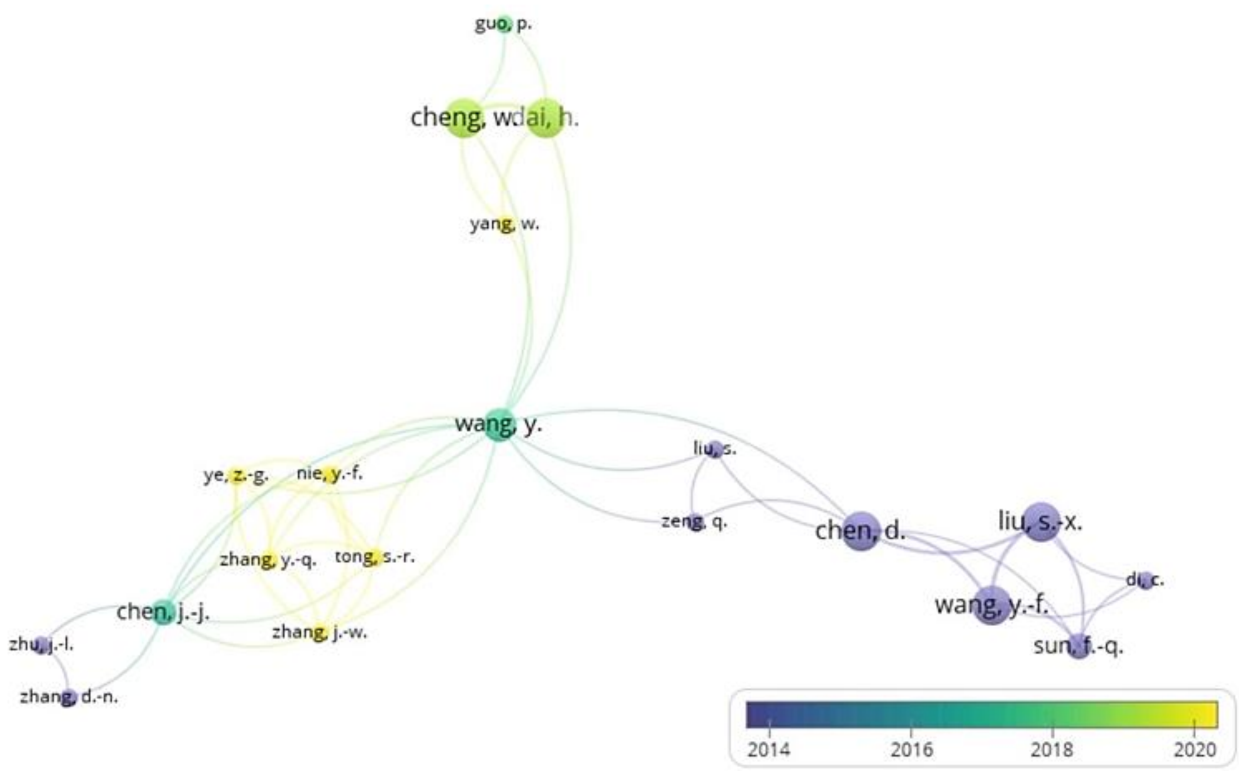


Fig. 5 Network visualization for co-authorship analysis

The cluster consists of authors who share similar research interests. The maximum number of edges between two authors is 25, indicating that they have co-authored a total of 25 papers. Furthermore, the co-authorship for the selected papers is robust, as each cluster is relatively large and is interconnected with other clusters, indicating a variety of researched topics with relatively few authors dominating this field of research.

Co-word Analysis

Co-word analysis is an additional method for analyzing the selected pool of papers, with the network for co-word analysis being generated using VOSViewer. This method examines the keywords used by the authors in the papers to determine their relationships and map them. The network is constructed using co-occurrence relationships, and co-word analysis aids in identifying the most relevant and significant keywords. From the pool of 171 documents, a total of 1188 keywords were extracted. For keyword occurrences to be included in the network, a minimum threshold value of 5 must be met. This yields a 73-keyword network comprised of 6 distinct clusters. Figure 7 depicts the co-word analysis network with 73 nodes and 1121 edges.

The size of a node is proportional to the number of occurrences it has with other nodes. The 6 clusters are color-coded, with the red cluster containing 23 keywords and 138 occurrences of the main keyword "scheduling". The second green cluster contains 18 keywords, with "project scheduling" appearing 70 times as the main keyword. The third blue cluster includes 17 keywords, with "resource-constrained projects" being the most prevalent with 45 occurrences. The yellow fourth cluster covers 8 keywords, with "scheduling algorithms" being the most prevalent with 13 occurrences. The purple fifth cluster has 5 keywords, the most frequent of which is "project scheduling problem" with 39 occurrences. The final pink cluster comprises 2 keywords, with "heuristic algorithms" being the most prevalent with 20 occurrences.

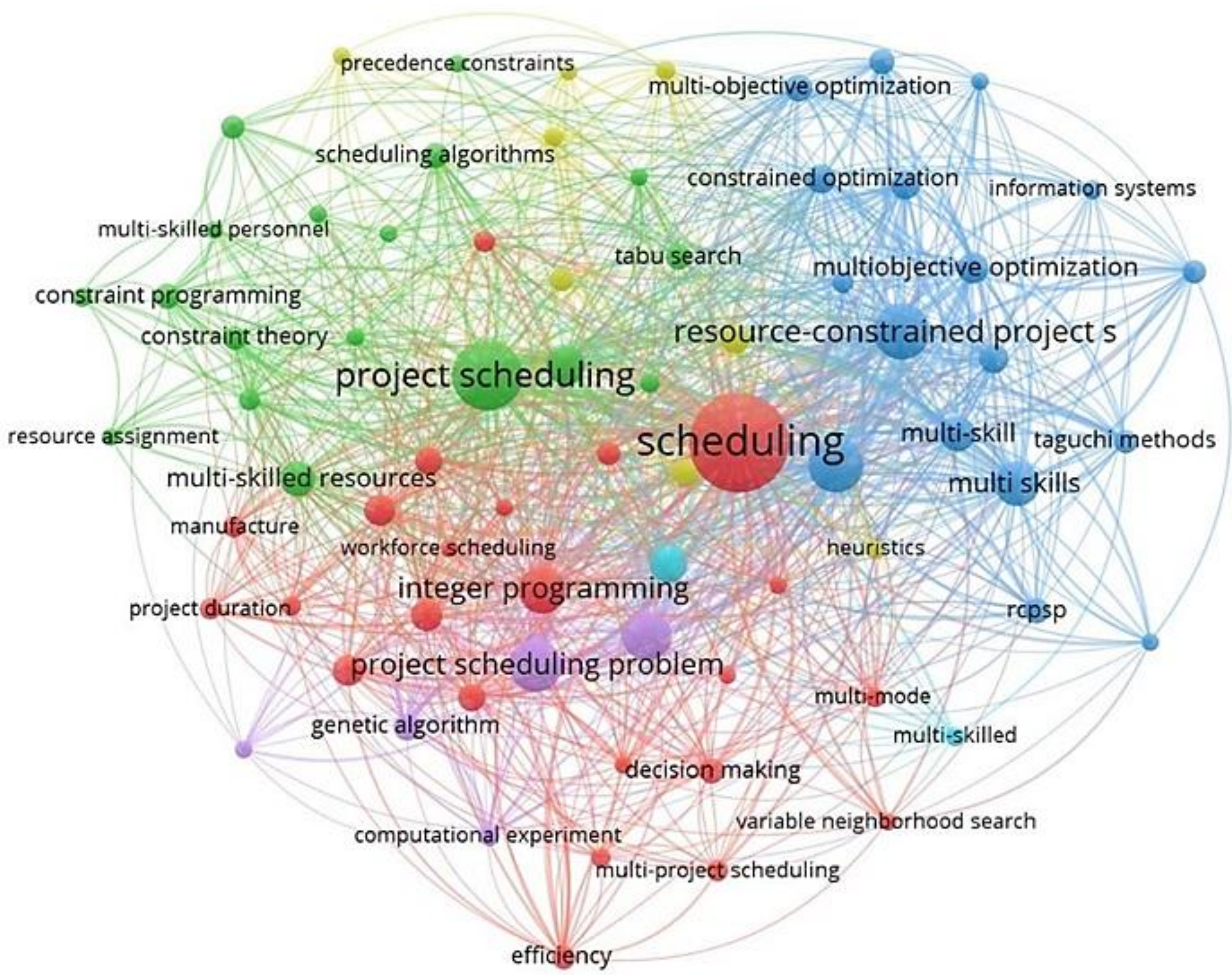


Fig. 6 Co-word analysis network

Co-citation analysis and data clustering

Co-citation analysis illustrates the connections between topics, journals, authors, and keywords. Moreover, it describes how they interact [139, 140]. The social relationship structure between authors is revealed by applying co-citation analysis to authors. Besides that, applying co-citation analysis to publications reveals the intellectual structure of the field of study [141]. The co-citation network generated by the analysis consists of nodes representing the articles and edges indicating the co-occurrence of these nodes in their reference lists [142]. The co-citation analysis is based on the papers cited in the pool of 171 papers. Additionally, it is essential to note that articles A and B are co-cited if both were cited by article C. Articles that are often cited by one another are likely to be connected in their field of study, as indicated by previous studies [143].

To initiate co-citation analysis, a network map was generated on Gephi using the network file generated by Bibexcel, where Gephi identified 473 co-cited articles within the sample. Initially, the map generated by Gephi was random and lacked patterns. Nevertheless, Gephi employs several algorithms to generate a variety of layouts. For example, Force Atlas is the most recommended force-driven algorithm due to its simplicity of comprehension and readability [112]. The Force Atlas algorithm generates a network where linked nodes repel, and linked edges attract. In addition, the algorithm relocates the most connected nodes to the center of the network and the least connected nodes to the edges. Gephi [119] allows for the modification of strength, repulsion speed, node size, and gravity, among other characteristics. Figure 8 shows the Force Atlas layout of the 473 nodes.

Articles with similar characteristics and from the same research field are grouped by data clustering [144]. To create a cluster, the nodes are configured such that the links between nodes within a cluster are denser than those between nodes in other clusters [142, 144, 145]. Clustering permits network analysis to discover thematic topics, patterns, and interdependencies between clusters. The concept of modularity measures the density of links within cluster nodes [146]. The default modularity tool in Gephi is based on the Louvain algorithm, which is described by Equation (2). The tool determines the modularity index of the partition, which is a scalar value between -1 and +1. The modularity index compares the density of links within a cluster to the density of links within other clusters. According to [146], the modularity index is defined as follows:

$$Q = \frac{1}{2m}\sum_{ij}\left(A_{ij} - \frac{k_i k_j}{2m}\right)\,\delta(c_i, c_j), \qquad (2)$$

where:

A_{ij} = Edge's weight between node i and j

$k_i = \sum_j A_{ij}$ = Sum of the weights of the edges attached to node i

c_i = Vertex i assigned community

$$\delta(u,v) = \begin{cases} 1 & \text{if } u = v \\ 0 & \text{otherwise} \end{cases}$$

$$m = \frac{1}{2}\sum_{ij} A_{ij}$$

In this study, the algorithm applied to the network of 473 nodes produced 13 clusters. Based on the number of nodes, six of the thirteen clusters were deemed to be the strongest in terms of cluster size. The positioning and interactions of the six major clusters are depicted in Figure 9. The modularity index of the network is 0.654, indicating a relatively high degree of interdependence between clusters.

In addition, Table 9 identifies and summarizes the top 10 papers within each cluster according to their co-citation PageRank score. Then, the content and research area of the top papers are evaluated to identify the key thematic research topics that define each cluster. The cluster classifications and details are presented in Table 10.

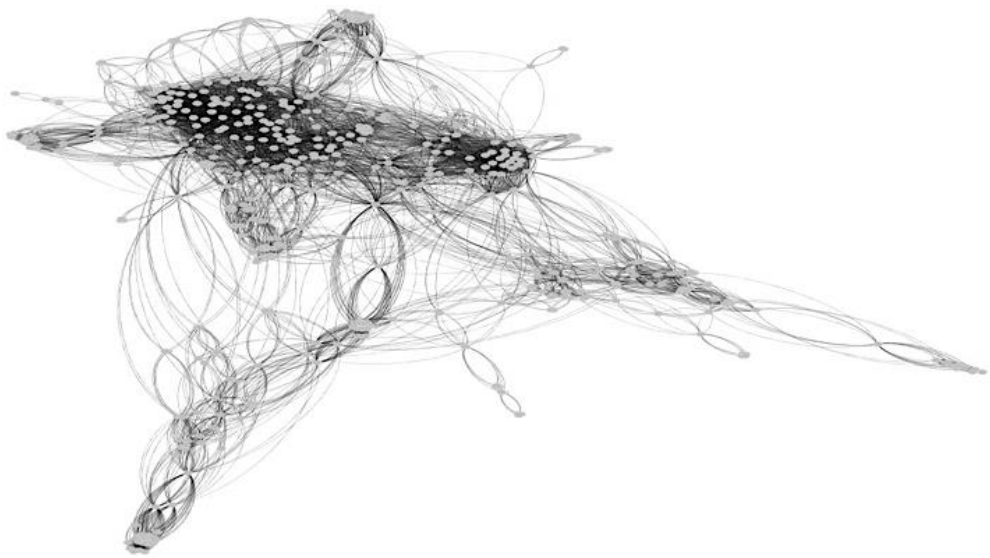
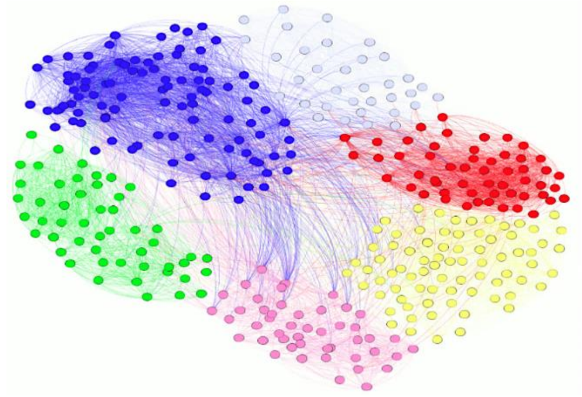


Fig. 7 The Force Atlas layout of the 473-node network



Cluster No.	Color
1	Blue
2	Yellow
3	Red
4	Green
5	Pink
6	Light Blue

Fig. 8 Network consisting of 6 clusters

Table 9
Top 10 papers for every cluster based on co-citation PageRank measure

Cluster 1		Cluster 2		Cluster 3	
(Hartmann and Briskorn 2010)	[3]	(Hartmann and Briskorn 2010)	[147]	(Kolisch and Padman 2001)	[148]
(Heimerl and Kolisch 2010)	[149]	(Li and Womer 2009)	[86]	(Alcaraz et al. 2003)	[150]
(Almeida et al. 2016)	[151]	(Correia and Saldanha-Da-Gama 2014)	[130]	(Hartmann, Sönke and Kolisch 2000)	[152]
(Gutjahr et al. 2008)	[153]	(Kolisch, Rainer and Hartmann 2006)	[154]	(Shadrokh and Kianfar 2007)	[155]
(Kolisch 1996)	[156]	(Brucker et al. 1999)	[157]	(Golenko-Ginzburg and Blokh 1997)	[158]
(Montoya et al. 2014a)	[41]	(Hartmann, Sönke and Kolisch 2000)	[152]	(Tiwari et al. 2009)	[136]
(Yannibelli and Amandi 2011)	[159]	(Bellenguez-Morineau 2008)	[128]	(Demeulemeester and Herroelen 1996)	[160]
(Gutjahr and Reiter 2010)	[72]	(Blazewicz et al. 1983)	[2]	(Heilmann 2001)	[161]
(Heimerl and Kolisch 2010)	[149]	(Drezet and Billaut 2008)	[162]	(Pritsker et al. 1969)	[163]
(Fırat and Hurkens 2012)	[127]	(Valls et al. 2008)	[164]	(Zhu et al. 2006)	[165]
Cluster 4		**Cluster 5**		**Cluster 6**	
(Liu and Wang 2012)	[80]	(Li and Womer 2009)	[86]	(Gomar et al. 2002)	[166]
(Arashpour et al. 2015)	[167]	(Drexl and Kimms 2001)	[168]	(Wongwai, Narongrit and Malaikrisa-nachalee 2011)	[138]
(Taguchi 1986)	[169]	(Kolisch, Sprecher and Drexl 1995)	[170]	(Hyari et al. 2010)	[171]
(Heimerl, C. and Kolisch 2010)	[149]	(Kolisch, Rainer and Hartmann 2006)	[154]	(Burleson et al. 1998)	[172]
(Hegazy et al. 2011)	[173]	(Valls et al. 2009)	[174]	(Gomar et al. 2002)	[166]
(Li and Womer 2009)	[40]	(Jain and Grossmann, 2001)	[175]	(Klein, 2000)	[176]
(Correi and Saldanha-Da-Gama 2014)	[130]	(Boctor 1996)	[177]	(Alwaer and Clements-Croome 2010)	[178]
(Montoya et al. 2014)	[41]	(Brucker et al. 1999)	[157]	(El-Rayes and Moselhi 2001)	[179]
(Andradóttir et al. 2013)	[180]	(Hooker 2002)	[181]	(Fernández-Sánchez and Rodríguez-López 2010)	[182]
(Arashpour et al. 2012)	[183]	(Kolisch, Sprecher and Drexl 1995)	[170]	(Jaśkowski and Sobotka 2006)	[184]

Table 10
Cluster classification and details

Cluster	No. of Papers	Area of Research
1	99	Workforce assignment and scheduling problems
2	78	Surveys, classification, extensions, and methods of resource-constrained project scheduling problems
3	54	Metaheuristics for resource-constrained project scheduling problems
4	50	Scheduling and staffing for multi-skilled workforce
5	47	Characterization and heuristics for of resource-constrained project scheduling problems
6	34	Assignment and scheduling of multi-skilled workforce in the construction industry

As pointed out previously, the papers listed in Tables 9 and 10 are all cited by the pool of 171 papers under investigation. The majority were published between the late 1990s and the beginning of the 2010s. A thorough evaluation of the top papers in Cluster 1 reveals an emphasis on the application of workforce assignment and scheduling problems. Several articles are devoted to the multi-skilled workforce scheduling problem. Concerning Cluster 2, it focuses primarily on various surveys, classifications, and extensions of the general RCPSP. In addition, it involves the investigation of numerous heuristics applicable to the same problem. In the third cluster, the leading papers develop a variety of metaheuristics, including GA for example, to solve the multi-mode RCPSP. Cluster 4 is primarily related to the scheduling and staffing of a multi-skilled workforce. The majority of the papers were published at the beginning of the 2010s, when researchers began investigating the multi-skilled workforce scheduling issue. The fifth cluster concentrates on the general RCPSP. A large number of the articles within this cluster were published in the early 2000s. The final cluster sheds light on project scheduling problems in the construction industry in specific

CONCLUSION

The MS-RCPSP is a project scheduling problem in which each activity requires a specific set of skills, and each resource being multi-skilled (e.g. cross trained workers or multi-purpose machines). The objective of MS-RCPSP is to schedule project activities and decide on resources-activities assignments while taking into account resource constraints such as limited availability of workers, equipment, and materials to minimize project duration, cost, or other criterion. MS-RCPSP has practical applications across a wide range of industries/areas, including IT/software development, manufacturing, healthcare, oil and gas, supply chain management, shutdown/turnaround maintenance, and construction. This paper provides a focused review of the literature and an exploration of the research trends of MS-RCPPSP in terms of performance measures, modelling and solution approaches, and area of application. In particular, it employs bibliometric and network analysis tools along with a systematic literature review to analyse a pool of 171 papers published between 2000 and 2021. The conducted analysis unveiled the top contributing authors, the most influential papers as well as the existing research tendencies and thematic research topics within this field of study. In principle, the MS-RCPSP is a complex and challenging problem that frequently requires the consideration of multiple performance measures to schedule tasks and allocate resources effectively. The most prevalent performance indicators are project completion time, project cost, and project tardiness, but other measures like multi-skilled staff assignment and schedule robustness are also essential. The MS-RCPSP has been addressed using various techniques to find optimal or nearly optimal solutions. These methods include exact approaches such as Integer Programming and Constraint Programming, Hybrid Benders Decomposition, and Branch and Price procedures. Additionally, approximate algorithms like GA have been employed. Various metaheuristics, including the VNS, path relinking, and cuckoo-search algorithms, have also been utilized. The selection of an approach depends on several factors such as the problem's size, complexity, and constraints. In addition, many studies have combined resource and time constraints to address the MS-RCPSP, with tardiness being a common consideration. Staffing scheduling problems, in particular, have also been widely addressed with time constraints. Upon utilizing systematic literature review approach coupled with bibliometric and network analysis, this work has identified the most influential works and unveiled research tendencies along with the existing research clusters and key contributing scholars within each cluster. This has enabled the identification of the existing research gaps and paved the way for highlighting a multitude of promising avenues for future research allowing researchers to focus their efforts into such unexplored areas.

RESEARCH GAPS

It is noted that the majority of existing research works commonly assume a fixed and static allocation of skills, overlooking the dynamic nature of skill requirements and availability within projects. To tackle this limitation, future research should place a higher priority on exploring dynamic skill assignment strategies capable of adapting to evolving project demands. These strategies ought to consider the varying skill demand and fluctuating availability of skilled workers. Furthermore, a common assumption among most research works is the deterministic nature of tasks durations, where those are fixed in advance. In reality, the durations of tasks may vary due to unforeseen reasons which may relate to resource availability, workers absenteeism, nature of the job, delay in a predecessor, quality checks, and shortage of material, among many others. As such, it is essential to incorporate uncertainty and risk management practices and adopt contingency planning when it comes to skill assignment and optimization processes. In particular, techniques on the likes of stochastic optimization, risk mitigation strategies, robust optimization and proactive-reactive scheduling should be integrated to come up with skill assignment plans that accommodate uncertainties in task durations, resource availability, and skill levels.

Furthermore, it is crucial to bridge the gap between existing literature and real-world constraints and practical considerations associated with skill assignment and optimization. Researchers should explore the integration of practical constraints such as skill certifications, regulatory requirements, and labour agreements. This can be achieved by incorporating these constraints into mathematical formulations or developing hybrid optimization techniques that consider both mathematical optimization and practical considerations. Additionally, there is a noticeable lack of empirical studies. Although several models and algorithms have been developed to solve the MS-RCPSP, more empirical studies are needed to assess the effectiveness of these models in addressing real-world project scheduling challenges based on realistic data drawn from a particular industry.

Despite the proven effectiveness of multi-objective optimization approaches to address MS-RCPSP, further research is necessary to address the conflicts that arise from diverse objectives. These objectives include minimizing skill gaps, maximizing resource utilization, minimizing skilled labor cost, reducing training expenses, and considering project-specific goals. To fulfil this need, researchers should explore innovative objective functions, assess the applicability of Pareto-based approaches, and incorporate decision-making practices that highlight the inherent trade-offs between multiple objectives.

In multi-project environments where resources are shared across different projects (portfolio management problem), collaboration and coordination mechanisms need to be investigated to optimize resource utilization and minimize conflicts between projects. Effective coordination, resource allocation strategies, and scheduling policies should be the focus of research in this area. Only few works have considered the portfolio management problem encompassing multiple projects in the presence of multi-skilled workers or general purpose machines/equipment highlighting the pressing need for further research along these lines. Moreover, the joint optimization of relevant decisions such as the ordering and lot sizing of the consumable recourses, supplier selection and routing decisions (e.g. for a construction project), alongside the classical activity scheduling and skill assignment decisions, pose unique challenges and bring the problem closer to reality.

FUTURE RESEARCH DIRECTIONS

With the increasing use of emerging technologies such as Artificial Intelligence (AI), Machine Learning (ML), and Internet of Things (IoT), there is a need to explore how these technologies can be leveraged in the context of MS-RCPSP models toward improving their performance and effectiveness. For instance, how can AI based algorithms be used to optimize the scheduling of multi-skilled resources in construction projects, or how can IoT sensors be used to monitor the progress of tasks completion and the availability of resources in a real-time basis while adjusting the project schedules accordingly. Indeed, the integration of ML based techniques offers a promising research direction to enhance the accuracy of resource demand prediction and project scheduling. By developing models that learn from historical project data and dynamically adjust schedules based on real-time resource availability, ML algorithms have a great potential towards improving scheduling effectiveness. However, existing studies often overlook uncertainty and variability in resource availability and project parameters, mainly focusing on deterministic scenarios (as noted earlier). To address this gap, future research should incorporate uncertainty modelling and probabilistic forecasting into ML based approaches.

Another research direction involves the hybridization of metaheuristic optimization techniques with ML methods. Hybrid algorithms that combine the strengths of both approaches can achieve more accurate and efficient project scheduling decisions while considering resource constraints and variability. For instance, GA can explore the search space ensuring the attainment of diversified solutions while ML techniques may assist in intelligent decision-making and learning from historical data.

Researchers can also explore hybrid scheduling approaches by combining different scheduling methodologies. By leveraging the strengths of rule-based algorithms, mathematical programming, and constraint programming, these hybrid approaches can effectively handle the complexity of multi-skilled resource-constrained projects and provide more robust scheduling solutions.

Investigating real-time scheduling approaches that dynamically adjust project schedules in response to changing circumstances is another valuable area of research. Algorithms that consider real-time resource availability, unexpected events, and emerging priorities can enable adaptive scheduling and efficient resource allocation. This research direction ensures that project schedules remain responsive and optimized in dynamic environments.

Finally, integrating sustainability considerations into project scheduling models and algorithms is an emerging research area. Optimizing resource usage and minimizing environmental impacts, such as energy consumption, carbon emissions, and waste generation, are pivotal contributors to more sustainable project scheduling practices. Additionally, it should be acknowledged that project scheduling is not solely a technical problem but also a social one. Therefore, research should also focus on how social factors such as teamwork, communication, leadership, and workers wellbeing can impact the effectiveness of MS-RCPSP models.

The aforementioned research directions seek to enhance the efficiency, accuracy, and applicability of MS-RCPSP techniques, enabling better management of complex projects with limited resources. By addressing the limitations of existing approaches and incorporating uncertainty and risk management aspects, researchers can improve the robustness and resilience of scheduling models. Integrating ML techniques and exploring hybrid scheduling approaches allow for more intelligent decision-making and effective handling of resource constraints and variability. Considering real-world constraints and practical considerations that capture the distinctive features of a particular industry better ensures the applicability of research findings to practical settings.

RECOMMENDATIONS FOR PROJECT MANAGERS

At the outset, it is crucial to acknowledge the existing gap between researchers and practitioners in the field of project management, particularly when it comes to addressing various practical aspects of the MS-RCPSP. Project managers, who wield a pivotal role in ensuring successful project execution, can play a crucial role in bridging this gap by fostering collaboration with researchers and demonstrating receptiveness to innovative approaches within this dynamic field. To promote knowledge exchange and bridge the researcher-practitioner divide, project managers and researchers should actively seek opportunities for collaboration and partnership, enabling the effective and practical application of research findings. Project managers stand to gain valuable insights from a multitude of research findings, including but not limited to the adoption of dynamic skill assignment techniques, proactive management of uncertainty and risk, the translation of theoretical models into practical settings, the utilization of multi-objective optimization strategies, exploration of hybrid scheduling methodologies, recognition of the significance of real-time scheduling approaches, incorporation of sustainability considerations, and the effective incorporation of social dynamics within project teams. By implementing these recommendations, project managers can adeptly navigate the complexities, enhance outcomes, and make significant contributions to advancing project scheduling practices within their respective industries.

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