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Mathematical Methods in Skills-based Workforce Scheduling: A Comprehensive Review

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Skills-based workforce scheduling is essential in enhancing operational efficiency across various industries. Despite its importance, a comprehensive review of mathematical methods used to address complex scheduling problems is still underexplored. Therefore, this paper aims to fill this gap by reviewing the research trends and the recent mathematical approaches that have been applied using both bibliometric and systematic review techniques. An initial dataset of 1109 articles was retrieved from the Web of Science (WoS) and Scopus databases and merged using Python software. After removing duplicates and non-English articles, 749 articles were analysed to identify the publication and citation trends, the most popular journals, the most cited articles, and the emerging keyword themes. To investigate the current mathematical methods of solving skills-based workforce scheduling, 62 articles that were published between 2020 and 2024 in the fields of operations research, management sciences, decision sciences, and mathematics were further analysed. The findings indicate that heuristic and metaheuristic approaches are the most commonly used, with hybrid approaches becoming more prevalent. This review offers valuable insights into the evolution of the landscape of mathematical techniques that may support future researchers in developing innovative concepts for workforce scheduling, which benefits both academic and practical applications in this field.

Keywords: skills-based scheduling; workforce optimisation; research trends; mathematical method trends

I. INTRODUCTION

Workforce scheduling has received significant attention, especially after the worldwide COVID-19 pandemic. The pandemic led to unpredictable staff absences and reduced workforce availability in various industries due to illness, quarantine requirements, travel restrictions, and health and safety concerns (Abu Hatab *et al.*, 2021; Gupta *et al.*, 2021). These challenges have introduced new considerations in optimising schedules, such as skills-based workforce scheduling.

Skills-based workforce scheduling is one of the scheduling methods that assigns workers to tasks not only based on their availability but also on their skill sets. This approach improves productivity and resource utilisation by matching tasks with the appropriate skills (Afshar-Nadjafi, 2021; Peña *et al.*, 2023; Snauwaert & Vanhoucke, 2023). As more organisations start to adopt this approach, mathematical techniques become essential to help decision-makers effectively align human resources with organisational goals. The solutions from the mathematical methods will then be incorporated into the scheduling system to support efficient workforce management.

Although the research on skills-based scheduling has been improved, there are key challenges in identifying the most relevant mathematical techniques to be used in specific

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scheduling problems. Therefore, to fill this gap, a comprehensive review of the mathematical methods that have been used in previous research is essential. The publication and citation trends, as well as keyword patterns, are also highlighted in this review to have a clearer understanding of the research field's evolution.

This study will analyse articles in the Scopus and Web of Science (WoS) databases that match the selected search keywords, aiming to address the following research questions (RQ):

RQ1: How do the publication and citation trends in the skills-based workforce scheduling research change over time?

RQ2: What are the top journals that most actively publish articles related to skills-based workforce scheduling research?

RQ3: How do the top journals impact the development of the field?

RQ4: What are the most cited articles that reveal the advancement of skills-based workforce scheduling research?

RQ5: What are the recent keyword research trends in this field of study (2020 to 2024)?

RQ6: What are the recent mathematical methods used to solve skills-based workforce scheduling problems in various sectors?

The structure of this paper is as follows: The first section reviews the general landscape of literature on skills-based workforce scheduling, including key definitions and fundamental concepts. Next, the methodology section outlines the bibliometric and systematic review approaches, including how data from Scopus and Web of Science were searched, selected, and analysed. This is followed by a detailed presentation of results and discussion section, where research trends, mathematical methods, and existing research gaps are highlighted. This paper will end with a conclusion section that summarises the findings and outlines future research directions that relate to skill-based workforce scheduling.

II. METHODOLOGY

The flow of this comprehensive review is illustrated in Figure 1. This study adopts a bibliometric approach to explore the research landscape of skills-based workforce scheduling, as well as a systematic review to analyse the recent mathematical techniques that applied to solve this type of scheduling problem. Data from two major academic databases, Scopus and Web of Science (WoS), were merged using Python software to ensure the inclusion of reliable and quality sources. The merged dataset was then analysed using Microsoft Excel, Publish or Perish (PoP) software, and VOSviewer to portray overall research trends.

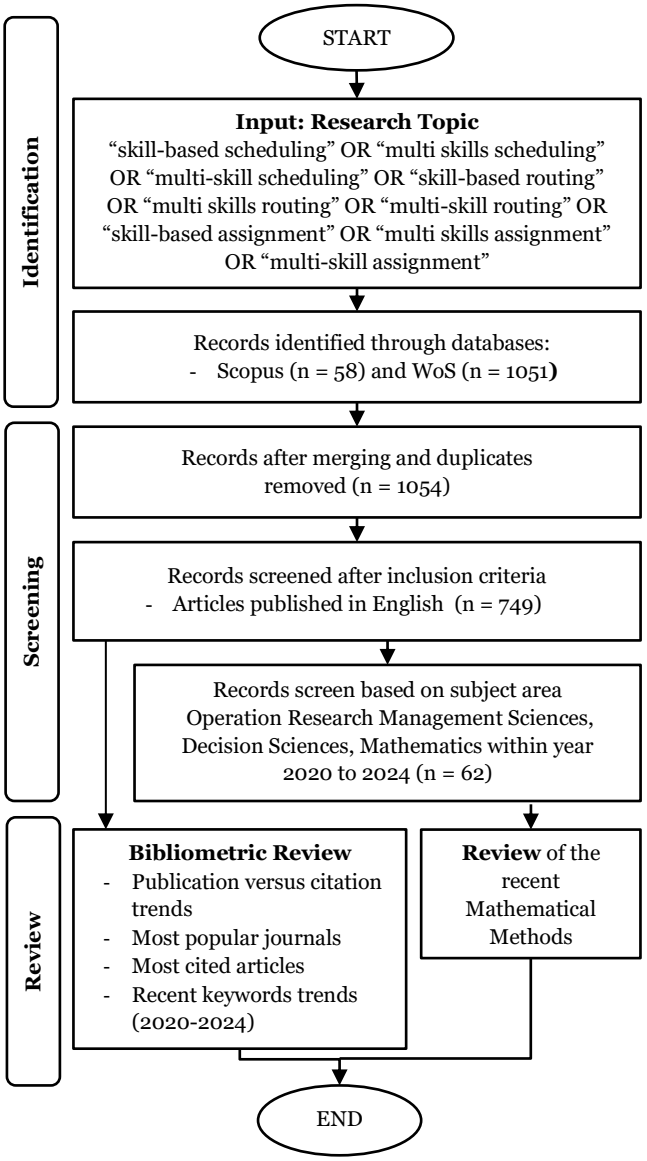

Figure 1. Methodology flowchart of this study

As shown in Figure 1, this study has three main phases: identification, screening, and review. The process begins by selecting specific keyword queries to search through the Scopus and WoS databases. This step is essential to ensure the inclusion of relevant documents in the initial search. The

chosen keywords were searched within the title, abstract, and keywords fields to increase the sensitivity of the search and reduce the retrieval of irrelevant documents (Gunwant, 2022; Sekulić *et al.*, 2022). According to Özdemir and Şahin (2023), keywords in academic articles serve as indicators of the main themes discussed.

This process is known as a systematic keyword search strategy. In literature reviews, it is essential to narrow down and only include the most relevant studies (Rahi *et al.*, 2022; Wan Othman & Abdullah, 2020). It also improves the understanding level of the research landscape (Hsu *et al.*, 2021; J. Wang *et al.*, 2020). Therefore, "skill-based scheduling", "multi-skills scheduling", "multi-skill routing", and "skill-based assignment" are the search keywords selected to be used in this study. As a result, the Scopus and WoS databases identified 58 and 1051 documents, respectively, as matching the selected search keywords.

During the second phase (screening), the documents retrieved from both databases were merged using Python software, and all duplicate documents were eliminated. Following this procedure, 1054 unique documents were obtained. Duplication of documents often occurs due to overlapping indexing across databases. For example, WoS may include the conference papers from Scopus and vice versa (Haryandi *et al.*, 2021; Y. Wang *et al.*, 2023). Thus, it is required to perform a de-duplication to ensure all retrieved datasets are unique records (Bokhari *et al.*, 2021; Groen *et al.*, 2020; Tavares *et al.*, 2021).

The merged records were then filtered to include only English articles, which narrowed the dataset to 749 articles. Bibliometric analysis was conducted based on these articles with the aim of exploring the overall research trends. Meanwhile, to examine the recent mathematical methods in solving skills-based workforce scheduling, a final dataset of 62 articles published between 2020 and 2024 in the fields of operations research, management sciences, decision sciences, and mathematics was selected.

In the last phase of this study, two types of reviews were conducted. First, a bibliometric review was performed to identify the citation patterns, publication trends, most-cited articles, popular journals, and recent keyword usage (2020 to 2024). Second, a systematic review of mathematical methods was carried out to highlight the common techniques that have been applied in solving skills-based workforce scheduling.

III. RESULTS AND DISCUSSION

Two types of reviews were conducted in this study (bibliometric and systematic reviews) to understand the research trends and the mathematical methods used in solving the skills-based workforce scheduling problems. On November 1, 2024, the dataset was retrieved from the Scopus and WoS databases, which will then be merged, deduplicated and sorted in the Python and Microsoft Excel software.

A. Bibliometric Review

Bibliometric analysis is a quantitative and systematic technique that allows assessing the advancement and influence of a research area in accordance with huge databases. It analyses publication patterns, citations, authorship behaviours, keyword distributions, and networks of collaborators using existing article metrics. This review method introduces new valuable data on themes and patterns of connections, based on which it is possible to trace the development within the field of study (Ahmad Sururi, 2022; Sarudin *et al.*, 2024). Thus, 749 articles will be used in this study to analyse the field using bibliometric analysis, focussing on trends in citations and publications, the most popular journals, and the most popular recent keywords.

1. Publication versus citation trends (RQ1)

To determine publication and citation trends, the Publish or Perish (PoP) software was used to analyse the citation metrics of the merged dataset after deduplication (1,054 articles) and a refined dataset (749 English articles). The metrics represent the academic influence and development of the research on skills-based workforce scheduling. The citation metrics of the initial and refined datasets are summarised in Table 1.

According to Table 1, the initial data (1054 articles) have obtained 14,235 citations at the average of 13.51 citations per paper. It demonstrates a broad and influential research landscape. Meanwhile, the refined dataset of 749 articles

recorded only 908 citations, or 1.21 citations per paper. This decrease indicates that the refined dataset is focused and specialised. Furthermore, despite being smaller, the refined dataset shows a slight increase in the number of authors per paper, rising from 3.68 to 3.8. This improvement suggests a slightly stronger collaboration among researchers after the refinement phase.

Table 1. Citation metrics comparison between initial and refined datasets.

	Initial	**Refined**
Number of papers	1,054	749
Publication Years	1993 – 2024	1993 - 2024
Total Citations	14,235	908
Cites per year	459.19	29.29
Cites per paper	13.51	1.21
Cites per author	4,764.19	407.22
Papers per author	395.62	272.33
Authors per paper	3.68	3.8
h-index	54	16
g-index	84	30
hI-norm	29	12
hI-annual	0.94	0.39
hA-index	16	5

Figure 2 illustrates the publication and citation trends for the refined dataset of 749 articles, highlighting periods of academic engagement and the growing interest in this field. As can be seen from Figure 2, both publications and citations from 1993 to 2005 remained below the average. The result indicates that during this period, there were limited publications and impact. However, starting in 2005, both metrics began to rise significantly, with notable peaks in 2010 and 2015. This upward trend indicates increasing academic interest and recognition of skills-based workforce scheduling as a relevant research topic.

The number of publications continued to rise steadily until 2020. Citation counts also followed an upward trend, although there were minor fluctuations. These patterns reflect an increase in scholarly engagement and the growing impact of key publications during this period. However, recently, the citation counts showed a drop due to several factors, including the ageing of highly cited articles, shifts in research focus, and disruptions caused by the COVID-19 pandemic. The pandemic shifted research focus and reduced productivity, as many researchers faced new challenges that may have affected both publication output and citation activity.

In conclusion, the refinement phase highlights the challenges of narrowing the research focus within the selected field. This phase is essential for identifying relevant articles by removing irrelevant and duplicate data. This ensures the accuracy and focus of the final dataset. Moreover, the publications and citation trends reflect the dynamic nature of scholarly engagement, showing how the publication volume can affect the citation and shape the direction of future research.

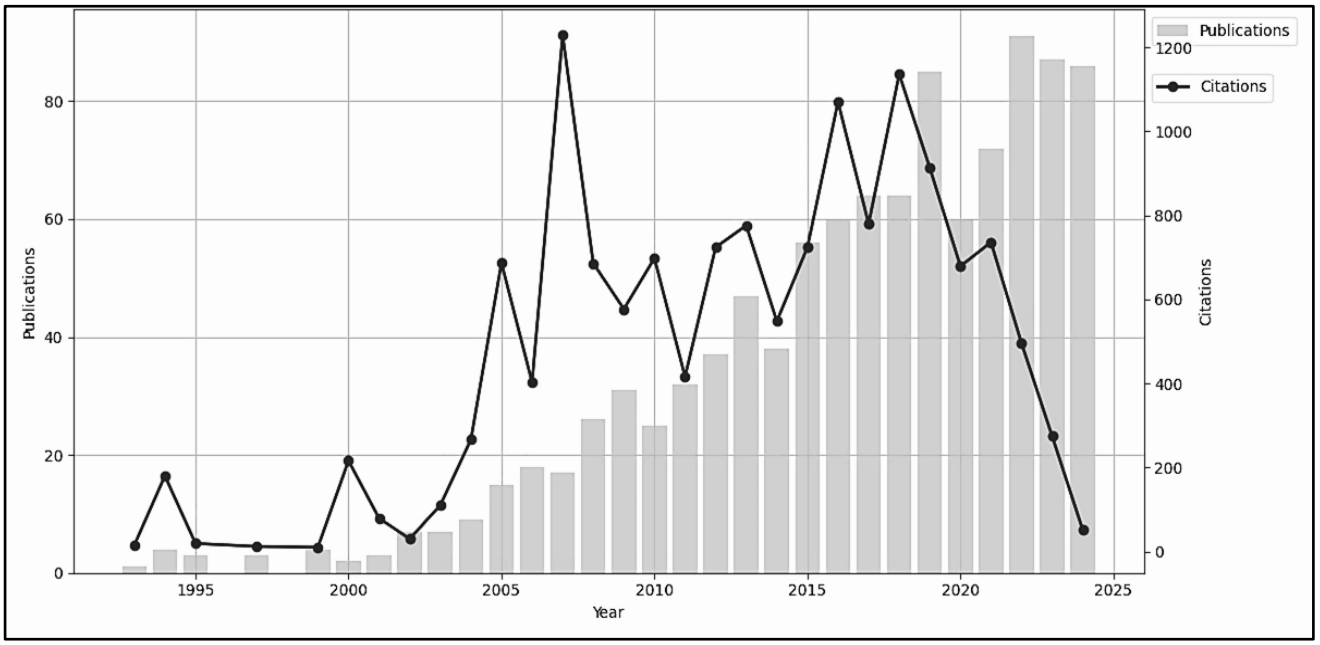

Figure 2. Publication versus citation trends for 749 articles

2. Journals that publish the most articles (RQ2 and RQ3)

Identifying the top journals in a specific field is valuable for future researchers because these journals usually have stronger citation metrics, reflecting greater research impact (Drivas & Kremmydas, 2020; Katherine Bosworth, 2022; Lei, 2022). High-ranking journals are also known for their credibility and reliability in publishing quality research articles. Therefore, identifying these leading journals can help researchers decide where to publish in order to enhance the visibility and credibility of their work within the academic community. Table 2 presents the top five journals that have published the most articles related to skills-based workforce scheduling, based on Scopus and WoS databases.

As shown in Table 2, the leading journal is "Computer & Industrial Engineering", published by Elsevier. It has received a high CiteScore of 12.7 with an impact factor of 6.7. This journal published 19 articles related to skills-based workforce scheduling research, with a total of 508 citations. The most frequently cited article in this journal is by Lian *et al.* (2018), with 85 citations. These data highlight the journal's major contribution to the field of industrial engineering and operations research.

The second top journal is "The International Journal of Production Research", published by Taylor and Francis. This journal published 18 articles related to skills-based workforce scheduling research. However, this journal received a higher CiteScore and more citations than "Computer & Industrial Engineering", with a 19.2 CiteScore and 499 citations. Subsequently, it had the highest impact factor (7.0) among the top journals on the list. The most cited article in this journal that related to this field was written by Heimerl and Kolisch (2010b) with 66 citations. In 2010, Heimerl and Kolisch published two articles related to multi-skilled workforce scheduling: one is about assigning multiple projects to the multi-skilled workforce, and the other addresses project assignment to heterogeneous workers while considering their learning, knowledge, and company skill level targets (Heimerl & Kolisch, 2010a, 2010b).

Following the list are the "European Journals of Operational Research" and "Annals of Operations Research", published by Elsevier and Springer, with 11 and 10 articles, respectively. In terms of CiteScore, both journals received 11.9 and 7.9, with an impact factor of 6.0 and 4.4, respectively. These differences were due to the total citations of their articles, with "European Journals of Operational Research" receiving 320 citations and "Annals of Operations Research" receiving 105 citations. The most influential articles in these journals were written by Cai and Li (2000), cited 99 times, and Eitzen *et al.* (2004), cited 59 times, respectively. Cai and Li (2000) proposed a genetic algorithm to solve a scheduling problem. It was formulated as a multicriteria optimisation model that considers different skill levels among staff. Meanwhile, Eitzen *et al.* (2004) solved a multi-skilled workforce optimisation problem at a

Table 2. The top five journals that actively published skills-based workforce scheduling researchs with highly cited articles.

No	Journal Name	Total papers	Total Citations	Cite Score	Impact Factor	Highly cited article	Times Cited	Publisher
1	Computers & Industrial Engineering	19	508	12.7	6.7	Lian *et al.* (2018)	85	Elsevier
2	International Journal of Production Research	18	499	19.2	7.0	Heimerl & Kolisch (2010b)	66	Taylor & Francis Ltd
3	European Journal of Operational Research	11	320	11.9	6.0	Cai & Li (2000)	99	Elsevier
4	Annals of Operations Research	10	105	7.9	4.4	Eitzen *et al.* (2004)	59	Springer
5	IFAC-PapersOnLine	9	128	1.7	1.05	Campos Ciro *et al.* (2016)	85	Elsevier

power station in Australia by proposing three solution techniques: the branch and price method, the column expansion method, and the column subset method. However, among these three methods, only the branch and price method consistently found optimal solutions for different dataset sizes.

Lastly, the fifth top journal is "IFAC-PapersOnline". Although it has a lower CiteScore (1.7) and impact factor (1.05), this journal is still relevant, with its most cited article, by Campos Ciro *et al.* (2016), receiving 85 citations. This article addressed a multi-objective optimisation problem in a real mechanical workshop, incorporating various resource constraints, such as the multi-skilled staff. These high citation count reflects the article's influence and its contribution to optimisation research. Overall, the presence of highly cited articles demonstrates how impactful research can enhance the visibility and credibility of the journals.

3. The most cited articles (RQ4)

While the most cited articles within the top five journals have been previously discussed, this section highlights the most cited articles across all sources, regardless of where the article was published. Identifying these influential articles can help future researchers recognise dominant trends and uncover potential gaps in previous studies.

Citation analysis is a key tool for evaluating the impact and relevance of scholarly research. It also can help to identify the prominent articles that have significantly shaped their field (Duan *et al.*, 2022; Y. Wang *et al.*, 2020). This analysis also reveals how the research topics have evolved and highlights the emerging topics that may encourage future innovation (Gao *et al.*, 2022; Martelli *et al.*, 2021). Furthermore, analysing highly cited articles helps identify prominent authors and institutions, which will encourage potential collaborative opportunities (He *et al.*, 2022; Lum *et al.*, 2020). Therefore, this study will analyse the top five most cited articles in the dataset, as summarised in Table 3.

This analysis will examine the refined dataset of 749 articles retrieved from the WoS and Scopus databases on 1st November 2024. The most cited article in this dataset was written by Xue *et al.* (2013), published in the Journal of Hydrology, with 265 citations and a contribution rate of 1.86%. This paper was among the first to explore the statistical assessment of the multi-satellite data for the Tropical Rainfall Measuring Mission (TRMM). This paper emphasises the importance of data-driven models, scenario testing, and predictive adjustments for optimising complex systems, all of which are highly relevant to workforce scheduling research.

Table 3. The top five most cited articles.

No	Article	Journal Name (Publisher)	Times Cited	Contribution rate (%)
1	Xue *et al.* (2013)	Journal of Hydrology (Elsevier)	265	1.86
2	Wallace & Whitt (2005)	Manufacturing and Service Operations Management (Informs)	176	1.24
3	Anshari *et al.* (2017)	Education and Information Technologies (Springer)	158	1.11
4	Berci and Morgenstern (1994)	Surgical Endoscopy-Ultrasound and Interventional Techniques (Springer)	142	1.00
5	Heimerl and Kolisch (2010a)	OR Spectrum (Springer)	141	0.99

The second-most cited paper, written by Wallace and Whitt (2005), proposed an algorithm for routing and staffing schedules in a call centre by considering the different skills of the agents. This paper considered two categories of agents: agents with limited skills and agents with full skill sets. Its main objective is to ensure optimal call routing while accurately determining staff requirements. Simulation experiments demonstrated that the developed

algorithm yields a nearly optimal solution. The paper's contribution lies in its practical applicability, particularly in service operations. It can improve workforce allocation and enhance responsiveness to customer demand. This article has received 174 citations, contributing 1.24% of the overall dataset.

Following the list of the most cited articles is a paper written by Anshari *et al.* (2017), with 158 citations, which contributed to 1.11% of the dataset. The study explores the effect of smartphone use in education, either as a learning aid or as a disruptive factor in the classroom. Although it was focused on the education sector, its implications of balancing technology and resource utilisation have wider effects on any optimisation systems, such as in the workforce scheduling and organisational productivity.

These highly cited articles offer important perspectives about the necessity of proper data analysis, the emergence of unique algorithms, and a balanced approach to resource allocation. These analyses not only contribute to advances in their respective fields but also provide important insights for optimising workforce scheduling and other resource management systems.

4. Recent keywords trend (2020 - 2024) (RQ5)

To identify and analyse recent trends in skills-based scheduling research, the dataset of 749 articles was filtered to include only articles published from 2020 to 2024 in the subject area of operations research, management science, mathematics, and decision sciences, as classified by the WoS and Scopus databases. This filtering resulted in 62 relevant articles (58 from WoS and four from Scopus).

Keyword co-occurrence analysis was conducted using VOSviewer software, applying the full counting method. Only keywords with at least three occurrences (in different documents) were included. The frequencies and relationships among these keywords were visualised using a network map (Sarudin *et al.*, 2024). This visualisation aims to highlight current themes and the research directions from the past five years.

In the keyword co-occurrence network map generated by VOSviewer, keywords are represented as nodes, with connections as links showing how often two keywords appear together. Several key metrics are provided in the map, such as the number of occurrences, total links, link strength, and total link strength. Larger nodes indicate more frequently used keywords, while thicker links represent stronger co-occurrence between two keywords. These connections reveal which topics are closely related, allowing researchers to identify emerging themes and collaboration patterns (Ito & Ohnishi, 2021; Kilpatrick *et al.*, 2023; Kato *et al.*, 2023; Moraes Pinto *et al.*, 2019; Wong *et al.*, 2023; Wu *et al.*, 2023).

As a result, 34 out of 386 keywords met the minimum occurrences threshold (three occurrences). These keywords were grouped into four clusters: Cluster 1 (9 items), Cluster 2 (9 items), Cluster 3 (8 items), and Cluster 4 (8 items). Each cluster represents different research themes within this field. The analysis also revealed 162 links among these keywords, with a total link strength of 224. This data indicates a strong thematic integration across topics. These connections are shown in the network map in Figure 3.

Among the 34 unique keywords, "algorithm" and "model" were the most often mentioned (10 times each), with total link strengths of 30 and 28, respectively. These were followed by "genetic algorithm" and "maintenance", which appeared nine times each, with a total link strength of 16 and 19. These popular terms reflect a growing reliance on computational approaches, such as optimisation algorithms, to solve complicated scheduling problems that involve numerous constraints and variables.

The keyword co-occurrence analysis has identified four distinct clusters that represent different aspects of the research landscape in skills-based workforce scheduling. Cluster 1, consisting of keywords such as "branch-and-price", "local search", "tabu search", "variable neighborhood search", and "optimisation", reflects the frequent use of optimisation methods in solving scheduling problems. The frequent appearance of these terms highlights the researchers' focus on enhancing algorithmic performance and solution efficiency in complex scheduling scenarios, particularly when facing constraints related to time, skill levels, and resource availability.

Cluster 2 consists of nine items, including "algorithm," "project scheduling", "assignment", "classification", "team formation", and "multi-skill". These keywords represent the trend toward flexible, adaptable scheduling methods that

are able to handle various scenarios. The keyword "multi-skill" specifically points to increased interest in designing a scheduling system that aligns tasks with individual competencies to optimise team productivity and worker performance.

Cluster 3 comprises eight keywords, such as "model" (10 occurrences, TLS: 28), "genetic algorithm" (9 occurrences, TLS: 9), "heuristics" (7 occurrences, TLS: 7), "allocation" (4 occurrences, TLS: 9) "maintenance scheduling" (3 occurrences, TLS: 4), "multi-objective optimization" (3 occurrences, TLS: 7), and "optimization algorithm" (3 occurrences, TLS: 6). This cluster is strongly associated with applied scheduling problems, particularly in maintenance scheduling. This problem has been solved using various mathematical methods, such as genetic algorithms, heuristics, and multiobjective optimisation. It demonstrates a methodological evolution that combines modelling techniques with algorithmic flexibility.

The last cluster, Cluster 4, which also had eight items, is categorised based on theoretical foundations such as "asymptotic analysis," "asymptotic optimality," and "queue." These keywords indicate a sustained interest in exploring the efficiency, scalability, and theoretical robustness of scheduling algorithms. This cluster underscores the role of analytical techniques in addressing large-scale and stochastic workforce scheduling problems, which are increasingly relevant in dynamic operational environments such as call centres, healthcare, and manufacturing.

In conclusion, the keyword analysis reveals four distinct research directions: the development of optimisation techniques in solving skills-based workforce scheduling (Cluster 1), the design of flexible and competency-based scheduling systems (Cluster 2), the application of advanced algorithms in real-world scheduling problems (Cluster 3), and the focus of theoretical insights for algorithm refinement (Cluster 4). These trends show the evolution of skills-based workforce scheduling from traditional approaches toward more intelligent, adaptive, and scalable systems. Understanding these themes not only helps identify current research gaps but also helps future investigations into algorithm development, real-time decision support, and hybrid scheduling frameworks that are capable of adapting to real-world challenges.

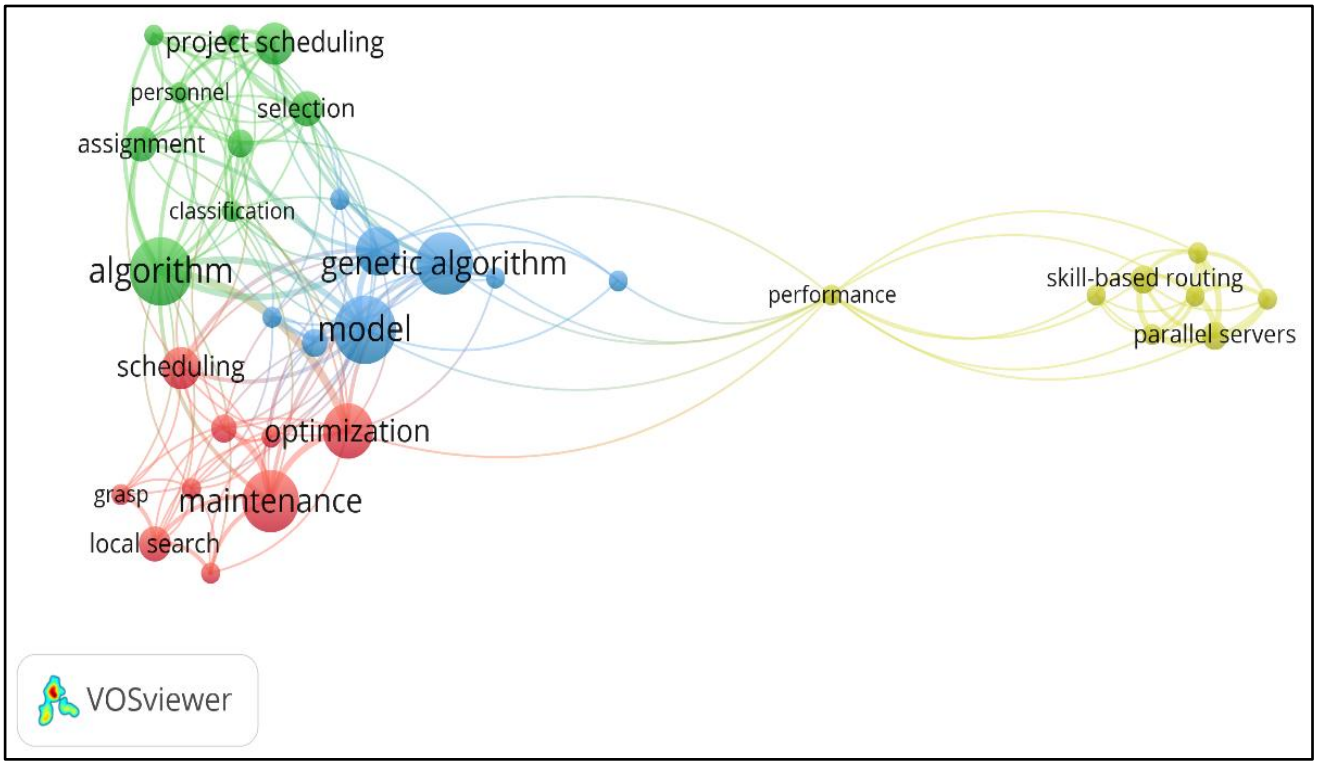

Figure 3. Recent keywords trend for 2020 to 2024 (Online map: https://tinyurl.com/284xq58p)

B. Review of Mathematical Methods (RQ6)

This section presents a review of recent developments in mathematical methods applied to skill-based workforce scheduling problems across various industries. To ensure a comprehensive and up-to-date analysis, relevant articles were retrieved from the Web of Science (WoS) and Scopus databases. Only English articles that were published between 2020 and 2024, which are classified in the subject area of Operation Research Management Sciences, Decision Sciences, or Mathematics, will proceed to be analysed in this section. After filtering, 62 articles were reviewed, with the 20 most recent studies summarised in Table 4, which highlighted three main methodological approaches: mathematical programming (MP), heuristic and metaheuristic (H_Mh), and multi-objective optimisation (MO).

As shown in Table 4, most studies adopted heuristic and metaheuristic methods, such as greedy algorithms (Polo - Mejía *et al.*, 2023; Torba *et al.*, 2024; L. Wang *et al.*, 2024), whale optimisation algorithms (Shan *et al.*, 2024), Lagrangian heuristic (Yan *et al.*, 2023), and genetic algorithms (Y. Chen & Wang, 2024; Damm *et al.*, 2024; Du & Li, 2024; Hatami-Moghaddam *et al.*, 2024; Lin *et al.*, 2020; L. Wang *et al.*, 2024). These results reflect the computational complexity of workforce scheduling problems, particularly in large-scale and real-world applications.

Furthermore, interest in multi-objective optimisation (MO) has grown. Nearly 30% of the reviewed articles used MO to address trade-offs between goals, such as cost, client satisfaction, and operational efficiencies. For example, in the study by Chaker *et al.* (2024), the authors optimised both personnel qualifications and client satisfaction, while Du and Li (2024) addressed caregivers' and customers' satisfaction. These studies illustrate a shift toward balancing operational performance with broader organisational and societal considerations.

The integration of real-life case studies is also observed in these recent articles. Many studies emphasise the practical applications of real-world datasets and scenarios. For instance, researchers have explored case studies in open-pit mining processes (Wiest-Goyeneche *et al.*, 2024), home healthcare routing and scheduling (Du & Li, 2024; Parreño-Torres *et al.*, 2024), and audit project management (X. Wang *et al.*, 2022; 2024). These examples reflect a growing trend in addressing industry-specific challenges through tailored scheduling solutions.

In summary, this review highlights the substantial progress and variety of mathematical approaches applied to skill-based workforce scheduling. The increasing adoption of multi-objective models, the dominance of heuristic and metaheuristic techniques, and the development of industry-specific applications demonstrate that the mathematical methods provide a solid foundation for enhancing workforce scheduling. These methods support solutions that are not only efficient and adaptable but also aligned with practical needs across various sectors.

Table 4. The top 20 most recent articles were published in the WoS and Scopus databases.

No	Articles	Solution method		
		MP	H_Mh	MO
1	Torba *et al.* (2024)	√		
2	Wiest-Goyeneche *et al.* (2024)	√		
3	Hatami-Moghaddam *et al.* (2024)		√	
4	Parreño-Torres *et al.* (2024)	√		
5	Chaker *et al.* (2024)		√	√
6	Shan *et al.* (2024)		√	
7	L. Wang *et al.* (2024)	√		
8	Damm *et al.* (2024)		√	√
9	Y. Chen and Wang (2024)		√	
10	X. Chen *et al.* (2024)		√	
11	Farboodi *et al.* (2024)	√		√
12	Du and Li (2024)		√	
13	X. Wang *et al.* (2024)			√
14	Castelletti *et al.* (2024)	√		
15	Haroune *et al.* (2023)		√	√
16	Hu *et al.* (2023)		√	
17	Polo-Mejía *et al.* (2023)		√	
18	Yan *et al.* (2023)		√	
19	Annear *et al.* (2023)		√	
20	X. Wang *et al.*(2022)		√	√

IV. CONCLUSION

The lack of a comprehensive review on skills-based workforce scheduling has caused uneven understanding and slowed progress in addressing complex scheduling challenges. To address this gap, this study provides both bibliometric and systematic analyses of mathematical methods applied to skills-based workforce scheduling. These analyses help uncover influential research trends, contributors and methodological developments in the field.

This study examined 1109 articles retrieved from the Scopus and Web of Science (WoS) databases. After filtering and merging the data using Python software, 749 English articles were selected for bibliometric analysis. This analysis explored publication and citation trends, leading journals, and the most cited articles, from 1993 to 2024. In addition, a keyword co-occurrence analysis was conducted on 62 articles published between 2020 and 2024, with 34 out of 386 keywords identified and visualised using a network map to highlight recent thematic developments.

In order to help future research in this area, this review also examines the mathematical methods that are frequently used in recent literature, including mathematical programming, heuristics, metaheuristics, or multi-objective optimisation approaches. Overall, the findings in this paper offer a strong foundation for researchers aiming to develop innovative and effective solutions for skills-based workforce scheduling, which will improve both theoretical and practical applications.

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