Examining the developments in scheduling algorithms research: A bibliometric approach

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HIGHLIGHTS
- Scheduling algorithms research has an annual scientific production growth rate of 16.62%.
- The keyword "scheduling" is the most relevant keyword. It has the highest betweenness centrality of 101.94.
- Buyya Rajkumar is the most productive author in scheduling algorithms research.
- Edge Computing is the most discussed topic concerning scheduling algorithms research in 2020 and 2021.
- Institutional collaborations have not been well-established in this field.

ABSTRACT
This study examined the developments in the field of Scheduling algorithms in the last 30 years (1992–2021) to help researchers gain new insight and uncover the emerging areas of growth for further research in this field. This study, therefore, carried out a bibliometric analysis of 12,644 peer-reviewed documents extracted from the Scopus database using the Bibliometrix R package for bibliometric analysis via the Biblioshiny web interface. The results of this study established the development status of the field of Scheduling Algorithms, the growth rate, and emerging thematic areas for further research, institutions, and country collaborations. It also identified the most impactful and leading authors, keywords, sources, and publications in this field. These findings can help both budding and established researchers to find new research focus and collaboration opportunities and make informed decisions as they research the field of scheduling algorithms and their applications.

1. Introduction
Scheduling is allocating resources to tasks to optimize certain performance measures such as waiting time, throughput, and makespan. The study of scheduling spans over 60 years in various fields such as Operations Research, Management, Computer Science, Industrial Engineering, and Health (An et al., 2012; Burdett and Kozan, 2018; Kumar et al., 2018; Sharma et al., 2021a, 2021b; Yan et al., 2021). Its advent in the field of Computer Science resulted from the need to solve scheduling problems arising from the development of the Operating Systems (OS) (Leung, 2004). The development of OS led to the need for efficient scheduling algorithms to manage computational resources such as CPU time, Storage, Memory, and I/O devices in computer systems. Some of the scheduling algorithms are First Come First Serve (FCFS), Shortest Job First (SJF), Priority scheduling, Shortest Remaining Time (SRT), Round Robin, Min-Min, Max-Min, and Multilevel queue. The major goal is to ensure fairness in allocating resources to tasks. Different variants of these algorithms have been developed (Chandiramani et al., 2019; Nazar et al., 2019; Omotehinwa et al., 2019a, 2019b; Sharma et al., 2021a) and the area of application of these algorithms cuts across different domains; load balancing in Cloud Computing (Das et al., 2017; Ghosh and Banerjee, 2018), cost minimization in fog computing, and energy-balancing in the Internet of Things (IoT) (Choudhari et al., 2018; Tychalas and Karatza, 2020). This study aims to carry out a bibliometric analysis of the developments of scheduling algorithms in the last 30 years. According to Verbeek et al. (2002), bibliometric analysis is "the collection, the handling, and the analysis of quantitative bibliographic data, derived from scientific publications". In science and applied sciences, bibliometric analysis has become an acceptable standard for descriptive and evaluative measures of the impact of research outputs. It is also a key

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component of research evaluation methodology (Ellegaard and Wallin, 2015). The use of bibliometrics in different disciplines has continued to increase. Studies similar to this study (Dao et al., 2017; Rahimi et al., 2022; Shishido and Estrella, 2018; Yu et al., 2018) have carried out a bibliometric analysis of the genetic algorithm, grids, and clouds, Cloud Computing Technology, and Non-dominated Sorting Genetic Algorithm II (NSGA II). The systematic review helps to gain new insight and uncover emerging trends, performance analysis, and social and intellectual structures from a field of study or topic.

For example, the result of a bibliographic coupling produced meaningful knowledge from cumulative data of a research field. This information can help both established and budding researchers in getting improved research results as the top keywords in this area can be identified quickly, most relevant authors, articles, and sources can guide on where to publish, top publications to review, potential research collaborators, emerging thematic areas can create a new focus for researchers. Existing survey papers have not focused on the general landscape or developments in this field. They have largely taken a narrow path that either focus on specific topics or area of applications of scheduling algorithms. These studies (Almansour and Allah, 2019; Arora and Banyal, 2022; Arunarani et al., 2019; Ghafari et al., 2022; Kumar et al., 2019; Sana and Li, 2021) focused on the extensive review of scheduling techniques in cloud computing (Agrawal et al., 2021; Davis and Burns, 2011; Olofintuyi et al., 2020), focused on the review of operating system scheduling algorithms while other studies such as (Maipan-Uku et al., 2017; Prajapati and Shah, 2014; Yousif et al., 2015) focused on scheduling in grid computing. A general overview of scheduling algorithms is necessary at this time to understand the trends over time and to discover a new research focus. It is also worthy of note that there is no study on bibliometric analysis of scheduling algorithms at the time of this writing. Therefore, this study is very important at this time.

### Table 1. Differences, advantages, and disadvantages of bibliometric analysis and systematic review study.

| Differences | Bibliometric Analysis Study | Systematic Review Study |
|-------------|----------------------------|-------------------------|
| - It is targeted at eliciting emerging trends, performance analysis, and social and intellectual structures from a field of study or topic. | - The goal is to analyze and summarize empirical studies to establish isolation or association in aims, methods, results, and variables from existing literature that supports generalizable knowledge or presents new research opportunities. |
| - It is applicable when the scope of review is wide. | - It is appropriate for the concept, method, and theory-specific reviews with a narrow scope. |
| - It relies on quantitative techniques and data. | - Qualitative techniques and data are used in a systematic review. |
| - A large amount of data is required. | - Small data is required. |
| - The analysis is done with software. | - It requires manual analysis and, in most cases, by more than one person. |

### Advantages

- The quality and quantity of research outputs, authors, sources, and institutions can be verified quickly with bibliometric analysis.
- The possibility for graphical visualization of results enhances the presentation and understanding of the results of the studies.
- Results of the bibliometric analysis are easily reproducible.

### Disadvantages

- The data repositories usually used in sourcing bibliographic data are not explicitly designed for bibliometric analysis; therefore, missing values or incorrectly entered data can affect the analysis results.
- Its quality measure is associated with parameters such as citation counts, h-index, and g-index, which cannot measure impacts in terms of breakthroughs in the field. A paper or author may have fewer citations but has groundbreaking research output.

### Table 2. Main information and summary of the dataset.

| Description | Results |
|-------------|---------|
| Timespan    | 1992–2021 |
| Documents   | 12,644 |
| Average years from publication | 8.88 |
| Average citations per document | 14.27 |
| Average citations per year per documents | 1,568 |
| References  | 245,972 |

| Document Types | Results |
|----------------|---------|
| Article        | 5,689 |
| Book           | 7 |
| Book chapter   | 98 |
| Conference paper | 6,802 |
| Erratum        | 1 |
| Review         | 47 |

| Document Contents | Results |
|-------------------|---------|
| Keywords Plus (ID)| 28,744 |
| Author's Keywords (DE) | 15,793 |

| Authors | Results |
|---------|---------|
| Authors | 17,958 |
| Author Appearances | 39,794 |
| Authors of single-authored documents | 580 |
| Authors of multi-authored documents | 17,378 |

| Authors Collaboration | Results |
|-----------------------|---------|
| Single-authored documents | 726 |
| Documents per Author | 0.704 |
| Authors per Document | 1.42 |
| Co-Authors per Documents | 3.15 |
| Collaboration Index | 1.46 |
understand the landscape of scheduling algorithms research, this study set out to answer the following questions:

i. What is the annual scientific production growth rate in scheduling algorithms research?

ii. What is the scientific production of authors? Which are the most relevant publications, most relevant sources globally and locally in scheduling algorithms research?

iii. What are the emerging, evolving, developed, and underdeveloped thematic areas in scheduling algorithms research?

iv. What is the country’s scientific production like? How established is the collaboration network of authors, institutions, and countries in scheduling algorithms research?

v. What are the trends in topics, top keywords, and co-occurrence network of keywords in scheduling algorithms research?

2. Methodology

The methodology used in this study is a bibliometric analysis which is a widely used methodology for the statistical evaluation of scientific outputs. The bibliometric analysis is done using Bibliometrix. Bibliometrix is an open-source science mapping analysis tool for statistical measurement of productivity within a research domain (Aria and Cuccurullo, 2017). According to Dervis (2019), “Bibliometrix is an R statistical package for analyzing and visualizing the bibliometric data from Web of Science and Scopus databases. It is written in R language, which operates under the GNU operating system”. It was developed by Aria, Massimo from the University of Naples, and Cuccurullo, Corrado from the University of Campania, both in Italy (Aria and Cuccurullo, 2017). Other bibliometric tools include Pajek, SciентoTex, CiteSpace, BibExcel, and VOSviewer. However, they are not as comprehensive, and the analysis is not easily reproduced as in Bibliometrix. Moral-Muñoz et al. (2020) stated that Bibliometrix is outstanding in the variety of analysis that can be carried out with it.

In this section, the standard workflow for bibliometrics: Study design, Data collection, Data analysis, Data visualization, and interpretation as presented in the study by (Zupic and Cater, 2015) and the procedure for bibliometric analysis itemized by (Donthu et al., 2021) was followed.

2.1. Study design

This study was designed to examine the developments in scheduling algorithms within the last 30 years, specifically from 1992 to 2021. The specific questions answered by this study are enumerated in section 1.

2.2. Data collection

The data used in this study were extracted from the Scopus database. Scopus is a repository for abstracts and citations of peer-reviewed literature such as Journals and conference proceedings. According to its blog (Scopus, 2020), Scopus is the largest of such repositories. The literature search process involves defining search strings containing keywords commonly used and/or related to scheduling algorithms research. The search string: (TITLE-ABS-KEY (“Scheduling Algorithm*”) AND TITLE-ABS-KEY (“Multilevel queue” OR “Round Robin” OR “Shortest Job First” OR “First Come First Serve” OR “Shortest Remaining Time” OR

| S/N | Year  | No. of Articles Published per Year | Percentage of No. of Articles Published Per Year | Cumulative growth of Articles Published Per Year | Cumulative Percentage of No. of Articles Published Per Year | Annual Growth Rate (AGR) of Published Articles Per Year (%) |
|-----|-------|-----------------------------------|-----------------------------------------------|-----------------------------------------------|-------------------------------------------------------------|----------------------------------------------------------------|
| 1   | 1992  | 8                                 | 0.06                                          | 8                                             | 0.06                                                        |                                                              |
| 2   | 1993  | 15                                | 0.12                                          | 23                                            | 0.18                                                        | 87.5                                                          |
| 3   | 1994  | 26                                | 0.21                                          | 49                                            | 0.39                                                        | 73.3                                                          |
| 4   | 1995  | 46                                | 0.36                                          | 95                                            | 0.75                                                        | 76.9                                                          |
| 5   | 1996  | 55                                | 0.43                                          | 150                                           | 1.19                                                        | 19.6                                                          |
| 6   | 1997  | 65                                | 0.51                                          | 215                                           | 1.70                                                        | 18.2                                                          |
| 7   | 1998  | 58                                | 0.46                                          | 273                                           | 2.16                                                        | -10.8                                                         |
| 8   | 1999  | 71                                | 0.56                                          | 344                                           | 2.72                                                        | 22.4                                                          |
| 9   | 2000  | 60                                | 0.47                                          | 404                                           | 3.20                                                        | -15.5                                                         |
| 10  | 2001  | 85                                | 0.67                                          | 489                                           | 3.87                                                        | 41.7                                                          |
| 11  | 2002  | 120                               | 0.95                                          | 609                                           | 4.82                                                        | 41.2                                                          |
| 12  | 2003  | 145                               | 1.15                                          | 754                                           | 5.96                                                        | 20.8                                                          |
| 13  | 2004  | 188                               | 1.49                                          | 942                                           | 7.45                                                        | 29.7                                                          |
| 14  | 2005  | 219                               | 1.73                                          | 1,161                                         | 9.18                                                        | 16.5                                                          |
| 15  | 2006  | 305                               | 2.41                                          | 1,466                                         | 11.59                                                       | 39.3                                                          |
| 16  | 2007  | 413                               | 3.27                                          | 1,879                                         | 14.86                                                       | 35.4                                                          |
| 17  | 2008  | 425                               | 3.36                                          | 2,304                                         | 18.22                                                       | 2.9                                                           |
| 18  | 2009  | 601                               | 4.75                                          | 2,905                                         | 22.98                                                       | 41.4                                                          |
| 19  | 2010  | 763                               | 6.03                                          | 3,668                                         | 29.01                                                       | 27.0                                                          |
| 20  | 2011  | 804                               | 6.36                                          | 4,472                                         | 35.37                                                       | 5.4                                                           |
| 21  | 2012  | 772                               | 6.11                                          | 5,244                                         | 41.47                                                       | -4.0                                                          |
| 22  | 2013  | 861                               | 6.81                                          | 6,105                                         | 48.28                                                       | 11.5                                                          |
| 23  | 2014  | 871                               | 6.89                                          | 6,976                                         | 55.17                                                       | 1.2                                                           |
| 24  | 2015  | 790                               | 6.25                                          | 7,766                                         | 61.42                                                       | -9.3                                                          |
| 25  | 2016  | 766                               | 6.06                                          | 8,532                                         | 67.48                                                       | -3.0                                                          |
| 26  | 2017  | 762                               | 6.03                                          | 9,294                                         | 73.51                                                       | 0.5                                                           |
| 27  | 2018  | 951                               | 7.52                                          | 10,245                                        | 81.03                                                       | 24.8                                                          |
| 28  | 2019  | 1,016                             | 8.04                                          | 11,261                                        | 89.06                                                       | 6.8                                                           |
| 29  | 2020  | 692                               | 5.47                                          | 11,953                                        | 94.53                                                       | -31.9                                                         |
| 30  | 2021  | 691                               | 5.47                                          | 12,644                                        | 100.00                                                      | -0.1                                                          |
|     |       |                                   |                                               |                                               | 12,644                                                      | 100                                                          |
"Priority queue" OR "Makespan" OR "average waiting time" OR "turnaround time" OR "Context Switch" OR "Completion time" OR "Resource allocation" OR "Time Quantum" OR "Grid computing" OR "Cloud Computing" OR "Edge Computing" OR "Fuzzy Computing" OR "Evolutionary Computing" OR "Green Computing") AND (EXCLUDE (SRCTYPE, "Unde
defined")) AND (EXCLUDE (PUBSTAGE, "AIP")) AND (LIMIT-TO (PUBYEAR > 1991 AND PUBYEAR < 2022)) AND (LIMIT-TO (LAN-
GUAGE, "English")) returned 12,881 documents. The wild card asterisk (*) ending the keyword “Scheduling algorithm” in the search ensures that 0 or more characters may complete the keywords. For example, “Scheduling algorithm*” means the search should select if available Scheduling algorithm or Scheduling algorithm s. There are Inclusion Criteria (IC), and Exclusion Criteria (EC) imposed on the search such that the result should include only documents written in the English language, excluding all articles in press "AIP". The 12,881 records were exported to CSV via the Scopus document search interface. It is impossible to export more than 2,000 records at a time; hence, the records were exported in batches and merged using Microsoft Excel. The web interface provided for no coding use of Bibliometrix called Biblioshiny was used to filter documents of type “Letter”, “Note”, “Editorial”, “Retracted”, and documents tagged 'Na N – No Author Name' were removed. Also, some of the documents with language; English/Croatia and English/Japanese, were removed. The filtering returned 12,644 documents analyzed in this study. The search was conducted on 21st March 2022. Table 2 presents the summary of the main information about the data. The literature in this dataset is composed of six types of documents which are Articles (n = 5,689), Book (n = 7), Book chapters (n = 98), Conference papers (n = 6,802), Erratum (n = 1), and Review papers (n = 47). Information about the document contents includes Author's Keywords (DE) and Keyword Plus (ID). The author’s keywords showed the total number of keywords contained in all documents. In contrast, the keywords plus is the total number of keywords generated by Scopus from titles, keywords, and

Table 4. Top 10 most productive authors in scheduling algorithm research.

| Authors             | No. of Articles | No. of Articles Fractionalized | No. of Articles as First Author | No. of Articles as Corresponding Author | Area of research interests                                      |
|---------------------|-----------------|-------------------------------|---------------------------------|----------------------------------------|---------------------------------------------------------------|
| Buyya, Rajkumar     | 65              | 21.07                         | 4                               | 4                                      | Cloud Computing; Virtual Machine; Edge Computing;             |
| Wang, Jibo          | 61              | 24.08                         | 30                              | 29                                     | Deteriorating Jobs; Scheduling Problems                       |
| Cheng, Tai Chiu     | 57              | 15.90                         | 11                              | 7                                      | Deteriorating Jobs; Scheduling Problem; Due Window; Supply Chain Coordination |
| Edwin               |                 |                               |                                 |                                        |                                                               |
| Yuan, Jinjiang      | 56              | 21.25                         | 4                               | 33                                     | Deteriorating Jobs; Scheduling Problem; Due Window; Batch Scheduling |
| Zandieh, Mostafa    | 47              | 16.75                         | 3                               | 35                                     | Flow Shop Scheduling; Fuzzy TOPSIS; Supplier Selection       |
| Zomaya, Albert Y.   | 46              | 12.71                         | 0                               | 3                                      | Cloud Computing; Edge Computing; Internet of Things; Location Awareness |
| Li, Kenli           | 43              | 10.88                         | 6                               | 18                                     | Task Scheduling; Heterogeneous Computing; DAG                  |
| Wu, Chin Chia       | 39              | 10.00                         | 8                               | 18                                     | Deteriorating Jobs; Scheduling Problem; Due Window; Flow Shop Scheduling |
| Fan, Quanke         | 37              | 10.28                         | 11                              | 17                                     | Flow Shop Scheduling; Makespan; Genetic Algorithm             |
| Wang, Ling          | 36              | 10.57                         | 7                               | 10                                     | Flow Shop Scheduling; Permutation Flowshop; Scheduling Problem |

Figure 1. Annual scientific growth of scheduling algorithms research.
abstracts of documents in this dataset (Aria and Cuccurullo, 2017). Other information includes the total number of authors in the entire document in this dataset, co-authors per document, and collaboration index. On successful cleaning of the data from Scopus, the function biblioshiny() was invoked in R studio to launch the biblioshiny web interface after loading the bibliometrix package with the function library("bibliometrix"). The CSV file containing the data extracted from Scopus was loaded through the biblioshiny interface. The Keyword Co-occurrence Network, Thematic Map, Collaboration Network, Trend Topics, Source, Document, and Author impact analyses were carried out.

2.3. Data analysis

The file containing the 12,644 documents was converted into bibliographic data frames for analysis after uploading through the Biblioshiny web interface accessed through the browser. In this study, descriptive analysis was carried out to determine the most relevant authors, most cited authors, and most productive countries based on the first author’s affiliation, top journals, and top keywords based on the frequency of occurrence. Citation analysis was done to determine the most cited references. Co-occurrence, collaboration, and co-word analysis were also carried out. The results are presented as networks.

2.4. Data visualization and interpretation

Data visualization and interpretation are presented in section 3.

3. Results and discussion

A preliminary analysis with a limited sample size yielded very different results. This implies that a sample size not large enough will lead to extremely biased results. Therefore, the sample size must be representative of the population size, and the methodology must be carefully designed to capture both broad and narrow themes in the field being researched. These will ensure negligible bias in the outcome.

In this section, the analysis results are presented based on the questions in the study design section.

3.1. What is the annual scientific production growth rate in scheduling algorithms research?

Table 3 shows the frequency of production for each year from 1992 to 2021. The highest number of production of publications in scheduling algorithm research was recorded in 2019, representing 8.04% (1,016) of the total number of publications. The sudden decrease in the number of publications in 2020 and 2021 could result from the global impact of the COVID-19 pandemic. The lowest annual growth rate of -31.9% was recorded in 2020 (Table 3).

It can be observed from Figure 1 that scheduling algorithms research has an annual scientific production growth rate of 16.62% (Eq. (2)). This growth rate is exponential and going by the “Rule of 70” (Eq. (1)) (Mahajan, 2021); this annual growth rate is expected to double in 4 years.

Rule of 70:

\[ t \approx \frac{70}{f} \]  

\[ t \] is the doubling time; \( f \) is the annual percentage growth rate.

The annual percentage growth rate is determined thus:

\[ \frac{\text{TCY} - \text{TPY}}{\text{TPY}} = \left( \frac{1}{2} \right)^{\frac{1}{f}} - 1 \]  

Where \( \text{TCY} \) is the total number of publications in the current year and \( \text{TPY} \) is the total number of publications in the previous year.
Table 5. Top 10 most cited publications based on local and global citations. The local citation measures the number of times each publication was cited by other publications within the dataset analyzed in this study. The global citations (total citations) measure the number of times each of the publications was cited across the entire Scopus database.

| Authors & Year of Publication | Publication Title | Scheduling Algorithms proposed/applied/reviewed/Hybridized | Source Title | Global Citations | Local Citations | Research Area |
|------------------------------|-------------------|----------------------------------------------------------|--------------|-----------------|-----------------|---------------|
| (Beloglazov et al., 2012)    | Energy-aware resource allocation heuristics for efficient management of data centres for Cloud computing | Modified Best Fit Decreasing (MBFD) algorithm | Future Generation Computer Systems | 1,943 | 153 | Virtual Machine | Data Center | Cloud Computing |
| (Yoo and Goldsmith, 2006)    | On the optimality of multi-antenna broadcast scheduling using zero-forcing beamforming | Round-robin Zero-Forcing Beamforming (ZFBF) and Proportional-fair ZFBF | IEEE Journal on Selected Areas in Communications | 1,609 | 16 | Beamforming | Multiuser MIMO | Block Diagonalization |
| (Buyya and Murshed, 2002)    | GridSim: A toolkit for the modelling and simulation of distributed resource management and scheduling for grid computing | Time-shared and Space-shared schedulers that runs allocation scheme such as First Come First Served (FCFS) and Shortest Job First Served (SJFS) | Concurrency and Computation: Practice and Experience | 1,087 | 147 | Computational Grids | Resource Allocation | Heterogeneous Computing |
| (Kwok and Ahmad, 1999)       | Static Scheduling Algorithms for Allocating Directed Task Graphs to Multiprocessors | Reviewed 27 Directed Acyclic Graph (DAG) scheduling algorithms such as Hu's Algorithm for Tree-Structured DAGs, Coffman and Graham's Algorithm for Two-Processor Scheduling, etc. | ACM Computing Surveys | 985 | 192 | Task Scheduling | Heterogeneous Computing | DAG |
| (McKeown, 1999)             | The iSLIP scheduling algorithm for input-queued switches | iSLIP: Iterative, Round-robin algorithm | IEEE/ACM Transactions on Networking | 984 | 48 | Switch | Multicast | Scheduler |
| (Buyya et al., 2009)        | Modelling and simulation of scalable cloud computing environments and the cloudsim toolkit: Challenges and opportunities | Time-shared and Space-shared algorithms for scheduling tasks and virtual machines. | Proceedings of the 2009 International Conference on High-Performance Computing and Simulation, HPCS 2009 | 755 | 118 | Cloud Computing | Data Center | Simulator |
| (Bini and Buttazzo, 2005)   | Measuring the performance of schedulability tests | Rate Monotonic (RM) and Earliest Deadline First (EDF) | Real-Time Systems | 581 | 8 | Schedulability Analysis | Computer System | Earliest Deadline First |
| (Leung, 2004)              | Handbook of scheduling: Algorithms, models, and performance analysis | Stochastic Scheduling | CRC Press | 560 | 5 | Production Control | Order Release | Job Shop |
| (Liu et al., 2016)          | Delay-optimal computation task scheduling for mobile-edge computing systems | Stochastic Computation Task Scheduling Policy | IEEE International Symposium on Information Theory - Proceedings | 479 | 30 | Edge Computing | Internet of Things | Location Awareness |
| (Dhinesh Babu and Venkata Krishna, 2013) | Honey bee behaviour inspired load balancing of tasks in cloud computing environments. | Honey Bee Inspired-Load Balancing (HBB-LB) algorithm | Applied Soft Computing Journal | 478 | 86 | Cloud Computing | Scientific Workflow | Execution Costs |
Table 6. The most relevant recent research is based on the total number of citations. The relevance of a research constituent, such as author, publication, source, institution, and so on, is measured by the frequency of document production and/or citations.

| Authors                  | Title                                                                 | Scheduling Algorithms Proposed/Applied/Reviewed/Hybridized | Source Title                        | Total Citation | Research Area                                      |
|--------------------------|----------------------------------------------------------------------|-----------------------------------------------------------|------------------------------------|----------------|---------------------------------------------------|
| (Chen et al., 2021)      | Uncertainty-Aware Online Scheduling for Real-Time Workflows in Cloud Service Environment | Uncertainty-Aware Online Scheduling Algorithm (ROSA)        | IEEE Transactions on Services Computing | 54             | Cloud Computing | Scientific Workflow | Execution Costs |
| (Goudarzi et al., 2021)  | An Application Placement Technique for Concurrent IoT Applications in Edge and Fog Computing Environments | Weighted Cost Model                                       | IEEE Transactions on Mobile Computing | 43             | Edge Computing | Internet of Things | Location Awareness |
| (Lv et al., 2021)        | Intelligent edge computing based on machine learning for smart city | Alternating Direction Method of Multipliers (ADMM) distributed task scheduling algorithm | Future Generation Computer Systems   | 39             | Edge Computing | Internet of Things | Location Awareness |
| (Gatti and Shivashankar, 2021) | Improved resource allocation scheme for optimizing the performance of cell-edge users in LTE-A system | Improved Resource Allocation Scheme (RAS) | Journal of Ambient Intelligence and Humanized Computing | 31             | Long Term Evolution (LTE) | Local Thermodynamic Equilibrium | Packet Scheduling |
| (Yuan et al., 2021)      | Be objective Task Scheduling for Distributed Green Data Centers      | Simulated-annealing-based Bioobjective Differential Evolution (SBDE) Algorithm | IEEE Transactions on Automation Science and Engineering | 31             | Virtual Machine | Data Center | Cloud Computing |
| (Yang et al., 2020a)     | Scheduling Policies for Federated Learning in Wireless Networks      | Random Scheduling (RS), Round-Robin (RR), and Proportional-fair (PF) | IEEE Transactions on Communications | 142            | Distributed Machine Learning | Function Computation | Federated Learning |
| (Liu et al., 2020)       | Distributed Set-Membership Filtering for Multirate Systems under the Round-Robin Scheduling over Sensor Networks | Round-Robin (RR) algorithm                                | IEEE Transactions on Cybernetics | 95             | Controller | Network-Induced Delay | Mean-Square Stability |
| (Yang et al., 2020b)     | Multi-UAV-Enabled Load-Balance Mobile-Edge Computing for IoT Networks | Deep Learning-based task scheduling algorithm             | IEEE Internet of Things Journal     | 52             | Drone | Unmanned Aerial Vehicles | Base Stations |
| (Cheng et al., 2019)     | Space/Aerial-Assisted Computing Offloading for IoT Applications: A Learning-Based Approach | Deep actor-critic-based online computing offloading algorithm | IEEE Journal on Selected Areas in Communications | 244            | Edge Computing | Internet of Things | Location Awareness |
| (Sundarraj, 2019)        | Optimal Task Assignment in Mobile Cloud Computing by Queue Based Ant-Bee Algorithm | Hybrid-Queue Ant Colony-Artificial Bee (Ant-Bee) algorithm | Wireless Personal Communications    | 200            | Edge Computing | Internet of Things | Location Awareness |
3.2. What is the scientific production of authors? Which are the most relevant publications, most relevant sources globally and locally in scheduling algorithms research?

In Table 4, the top 10 most productive authors in the scheduling algorithms research are based on the number of publications and contributions of authors to a publication. Fractional counting measures the contributions of authors to publications with more than one author (Sivertsen et al., 2019). In normalized fractional counting (Sivertsen et al., 2019), for an n-authored paper, the contribution of the author is $\frac{1}{n}$. The sum of the fractional contribution of the author for all papers by the author is the number of articles fractionalized. For example, in the last two years, an author has had a publication with four authors and another publication with three authors. The number of articles fractionalized is $0.25(\frac{1}{4}) + 0.33(\frac{1}{3}) = 0.58$.

The first or lead author of a research article is considered the most valuable contributor. In contrast, the corresponding author is the most senior researcher or principal investigator who owns the design for

Figure 3. Top 10 Most relevant sources based on the number of publications. The number of publications determines the intensity of the colour of the ball and its size; deeper colour and bigger size indicate a higher number of publications.

Figure 4. Top 10 Most locally cited sources. The local citation measures the number of times each source was cited by publications within the dataset analyzed. The number of publications determines the intensity of the colour of the ball and its size; deeper colour and bigger size indicate a higher number of publications.
which the research was carried out. The corresponding author, in most cases, is usually the first or the last author of a research article. However, in a recent study by Yu and Yin (2021), the findings revealed that an increase in the number of authors in an article decreases the first or last author’s chances of being the corresponding author. From Table 4, Wang J.-B is the most valuable contributor, with 30 articles as the first author and 29 as the corresponding author. Assuming that the contributions of all authors are equal through fractional counting, Wang J.-B has the highest number of articles fractionalized. Yuan J and Zandieh M have 33 and 35 articles as corresponding authors, suggesting that they are senior researchers in this field and supervised most of the research they co-authored. Buyya R is the most productive, with a total of 65 articles. It is essential to point out that the total number of publications count for each author was based on author ID and not the frequency of appearance of names on each document. It is impossible to uniquely identify authors by name as two or more authors could have the same last name and initials and be counted as one author.

In Figure 2, the top ten authors’ production over time is shown. The bubble size indicates the number of documents produced per year by the authors. The lines represent the span of production over time (timeline). The number of citations determines the intensity of the colour of the bubble, and deeper colour indicates higher citations. From Figure 2, it

Table 7. Top 10 most productive countries based on the frequency of appearance in publications in scheduling algorithms research.

| Country  | Continent | Frequency of Appearance | Total Citations | Average Article Citations |
|----------|-----------|-------------------------|-----------------|---------------------------|
| China    | Asia      | 14,055                  | 44,248          | 13.36                     |
| USA      | North America | 4,581                | 25,807          | 28.71                     |
| India    | Asia      | 4,464                   | 8,585           | 9.81                      |
| Iran     | Asia      | 1,282                   | 10,449          | 25.61                     |
| South Korea | Asia     | 1,065                   | 3,567           | 11.51                     |
| France   | Europe    | 1,059                   | 3,985           | 13.59                     |
| Canada   | North America | 912                    | 3,477           | 16.40                     |
| UK       | Europe    | 765                     | 2,381           | 16.42                     |
| Germany  | Europe    | 743                     | 2,751           | 16.47                     |
| Japan    | Asia      | 721                     | 1,501           | 10.01                     |
can be observed that Buyya R has the longest timeline (2001–2021) and has been consistent in scheduling algorithms research. He published three articles and recorded 193.8 total citations per year in 2012. He has an H-index of 30 based on the available data, which makes him the most impactful author in this field. The highest number of publications (13) in a year were recorded by Zandieh M and Wang J.-B in 2009 and 2010. The size of the bubbles indicates this for these years. However, Zandieh has the shortest span from 2008 to 2014.

Li K. has produced 43 documents, and he has an H-index of 26 and one publication in this field in 2021.

Table 5 revealed the top 10 most cited publications locally and globally. In this study, the relevance of a research constituent, such as author, publication, source, institution, and so on, is measured by the frequency of document production and/or citations. The local citation measures the number of times each publication was cited by other publications within the dataset analyzed in this study. The global citations (total citations) measure the number of times each of the publications was cited across the entire Scopus database. The global citation also indicates the degree of relevance of a particular publication to other fields of study. The study by Beloglazov et al. (2012) is the most significant and impactful to other fields as it has the highest number of global citations (1,943) on the top 10 list while the study by Kwok and Ahmad (1999) is the most locally cited by documents within the analyzed dataset.

Interestingly, the most productive author in this field, Buyya Rajkumar from the University of Melbourne, Australia (See Table 3), co-authored three (3) publications in the top 10 list of most cited publications. Also, all publications on the list have more global citations than local citations, which is ideal. This indicates that the publications are not only relevant and impactful to scheduling algorithms research but other fields. Content analysis of the literature presented in Tables 5 and 6 was carried out to determine the proposed, applied, or reviewed scheduling algorithms.

Citation is one of the most popular metrics often used to measure the impact of an article in its field (Aksnes et al., 2019). Therefore, in a bid to examine recent research in this field that has gained momentum and relevance, using citation count as a measure of impact, the top 5 articles in 2021, the top 3 in 2020, and the top 2 in 2019 are presented in Table 6. These articles are (Chen et al., 2021), (Yang et al., 2020a; 2020b), and (Cheng et al., 2019), the top most cited in 2021, 2020, and 2019 respectively. Their broad research areas are Cloud Computing, Distributed machines, Internet of Things, Packet Scheduling, and Edge Computing.

The top 10 most relevant sources based on the number of published documents are presented in Figure 3. Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) published 641 articles, has a total global citation count of 4,607 based on available data, and it has the highest number of publications by any source in this dataset. It has an H-index of 28. The global citation measures the number of citations received by each source in the entire Scopus database. The most cited sources locally (Figure 4) measure the number of citations received by each document within the documents in the dataset used in this research which spans 1992 to 2021.

3.3 What are the emerging, evolving, developed, and underdeveloped thematic areas in scheduling algorithms research?

The thematic structure of themes in scheduling algorithms research is shown in Figure 5. The co-word analysis network and cluster are based on Cobo et al. (2011) study. The bibliometrix function thematicMap() received the following parameters: Field = “ID”, No. of words = 500, No of Labels = 10, Minimum cluster per frequency per thousand documents = 5, Label size = 0.3, Clustering Algorithm = “Louvain”, layout = “Auto”.

Figure 6. Social structure: Authors’ collaboration network in scheduling algorithm research. The edges show that the connected authors have published at least two documents together. The size of the nodes indicates the number of documents published by the author in collaboration, and the thickness of the edges indicates the frequency of collaboration; a thicker edge means more collaborations between the connected authors (nodes).
To avoid bias, the keywords in the search query (Scheduling Algorithm; Scheduling Algorithms; Multilevel queue; Round Robin; Shortest Job First; First Come First Serve; Shortest Remaining Time; Priority queue; Makespan; average waiting time; turnaround time; Context Switch; Context Switches; Completion time; Resource allocation; Time Quantum; Grid computing; Cloud Computing; Edge Computing; Fuzzy Computing; Evolutionary Computing; Green Computing) were exempted from the co-word analysis and clustering. The clusters are generated from Keyword Plus (ID); author keywords, keywords in articles, and other important keywords within the abstract of the literature. The thematic map provides a clear interpretation of connections between themes (Grivel et al., 1995). The thematic map presents a visualization of the semantic strength of the themes’ internal (correlation between concepts) and external (cohesiveness of nodes) association, which are measured as density and centrality, respectively. A thematic map helps to identify the important concepts within a field. The upper-right quadrant (Q1) shows the driving or motor themes, the lower-right quadrant (Q2) shows the basic themes, the lower-left quadrant (Q3) shows the emerging or declining themes, and the upper-left quadrant (Q4) shows the developed themes less used and possibly understudied in this field. Figure 5 revealed that the themes such as multitasking, task-scheduling and energy utilization in the green cluster are the most important (high centrality) in scheduling algorithm
research. The cluster is intercepted by the motor theme (Q1) and Basic theme (Q2), which indicate that they are fairly developed.

The themes in the blue cluster are characterized by low density and centrality, which shows that they are underdeveloped and are fairly important in scheduling algorithm research. The themes are likely to move towards Q3 over time. This means they are likely to keep declining.

The trend analysis in Figure 9 also shows that the themes are not recurring in recent times. The size of the cluster also indicates that there are a few themes in this category. Scheduling is connected to other concepts such as optimization, genetic algorithms, heuristic algorithms, computational complexity, and heuristic methods in Q4. The cluster is characterized by high density and low centrality. Hence, they are well...
developed. These concepts are less used and possibly understudied in scheduling algorithms.

3.4. What is the country’s scientific production like? How established is the collaboration network of authors, institutions, and countries in scheduling algorithms research?

Table 7 revealed that China is the leading country in scheduling algorithms research, with 14,055 appearances on documents within the analyzed datasets and a total of 44,248 citations. Authors from the United States of America appeared 4,851 times, with a total citation count of 25,807 and an average article citation of 28.71. It is also interesting that three continents (with indigenous human populations), Africa, Oceania, and South America, are not represented in the top 10 countries leading research in scheduling algorithms.

The network diagrams in Figures 6, 7, and 11 were generated based on an unsupervised community detection clustering algorithm called the Louvain algorithm (Blondel et al., 2008). Other parameters set include number of nodes = 50, minimum number of edges = 2, normalization = association, remove isolated nodes = yes, layout = Auto. These parameters could be passed to the network function in bibliometrix through R or biblioshiny interface. In this study, they were passed through the biblioshiny web interface. The authors’ collaboration network analysis is presented in the network graph in Figure 6. The network graph comprises nodes that represent the authors and edges that indicate connections (links) between the authors. The edges show that the connected authors have published at least two documents together. The size of the nodes indicates the number of documents published by the author in collaboration, and the thickness of the edges indicates the frequency of collaboration; a thicker edge means more collaborations between the connected authors (nodes). Figure 6 revealed that Zomaya A. Y. from the University of Sydney and Lee Y. C. from Macquarie University, both from Australia, have well-established collaborations. A well-established collaboration can also be seen between Wu C.-C from Feng Chia University, Taiwan, and Yin Y. from Kunming University, China, as indicated by a thicker edge connecting the authors. Wang L. from Tsinghua University, China, and Wang J.-B from Shenyang Aerospace University, China, are the biggest facilitators of collaborations in the green and red cluster of nodes with a betweenness centrality of 193.16 and 193.63, respectively. The authors’ collaboration is quite sparse, and Table 2 reported a collaboration index of 1.46, which is quite low. The geographical proximity of authors largely facilitates collaborations.

Figure 7 also shows that institutional collaborations are established by the geographical proximity of institutions. Connections are largely between institutions within the same country. All the institutions clustered in green colour are based in Iran, institutions dominate the ones in purple from Australia, the pink clusters are institutions in China, and the red cluster is also dominated by institutions in China save for the collaborations established with the National University of Singapore. Shenyang Aerospace University and the Dalian University of Technology both in China have well-established collaborations. Some of the most relevant institutions in this field in terms of the number of articles published are Tsinghua University, China, Beijing University of Posts and Telecommunications, China, Islamic Azad University, Iran, National

Figure 11. Keywords co-occurrence network in scheduling algorithms research. The edges connecting the keywords (nodes) depict an established relationship between the connected nodes. A thicker edge indicates a high frequency of co-occurrence of the connected keywords in multiple documents.
University of Defense Technology, China, Hunan University, China with a total of 362, 360, 242, 223 and 221 articles published respectively.

In Figure 8, countries’ collaboration maps are shown. Only countries with at least five documents are shown on the map. It can be observed that there exists a well-established collaboration between China and the United States of America, as indicated by the thick line connecting the two countries. Australia also has a well-established collaboration with China. The collaboration between Egypt and Saudi Arabia, Australia and Jordan, India and China, Japan and Poland, India and Australia, and the United States of America and Brazil are not expressive, as indicated by the thin lines connecting the countries.

3.5. What are the trends in topics, top keywords, and co-occurrence network of keywords in scheduling algorithms research?

Keywords analysis helps to understand the trends in topics and concepts that are gaining attention in a research field. The results of the keyword analysis are shown in Figures 9 and 10. The trend topic analysis was carried out on the keywords in the titles of articles only. Minimum frequency = 50, No. of words per year = 5, Word Stemming = No; the Bigram frequency measure was used to count how often a pair of keywords co-occur. Figure 9 revealed the trends in topics for each year between 2004 and 2021. The years before 2004 did not have pairs of words with a frequency greater than or equal to 50, so they were not captured in the result. Packet scheduling, fair scheduling, and real-time scheduling were the trending topics between 2004 and 2007, with packet scheduling most discussed. The pair of words with the highest frequency (indicated by the biggest bubble in 2015) in all publication titles are Scheduling Algorithm, with a frequency of 1,560. Figure 9 also revealed that Edge Computing is the most discussed and trend topic concerning scheduling algorithms research in 2020 and 2021. Researchers, especially the young ones interested in scheduling algorithms research, can start looking at edge computing to identify new problems in this area that are gaining the attention of other researchers that could be addressed from the scheduling algorithms perspective. The result also showed that studies on Scheduling Algorithms research covered diverse research areas such as Cloud data, Reinforcement Learning, Ant Colony Optimization, Virtual Machines, Edge Computing, Mobile Edge, and so on. It can be observed (See Figure 9) that there has been a continuous increase in the number of keywords over the years, and it peaked around the year 2017. This implies that there has been a rapid knowledge expansion in this field.

The word cloud shown in Figure 10 further revealed the most frequently used and most relevant keywords in scheduling algorithms research. The size of a keyword is determined by its frequency of occurrence in the entire dataset. The word cloud was generated from Author Keywords (DE), publication titles, and abstracts. This collection is referred to as Keyword Plus (ID) in the Biblioshiny interface. Other parameters are Word occurrence = Frequency, Shape = Circle, Ellipticity = 0.65, Padding = 1, Font size = 1, Font type = Impact. The top three most relevant keywords in scheduling algorithms research are scheduling (Freq = 6,795), resource allocation (Freq = 2,136), and cloud computing (2,135), the reason why these keywords are bigger than others in the word cloud. Other relevant keywords in the scheduling algorithms research include makespan, optimization, algorithms, multitasking, and quality of service.

Keywords Co-occurrence Network (KCN) is essential for gaining new insight into a field based on the patterns and links of co-occurring keywords in analyzed literature (Radhakrishnan et al., 2017). The keywords co-occurrence network was generated based on the Louvain clustering algorithm. The Keyword Plus, which comprises keywords in Titles, Abstract, and Author keywords, were clustered. Other parameters are as stated in Figures 6 and 7. Figure 11 shows the KCN in scheduling algorithms research. The KCN is composed of nodes (Keywords) and edges (links). The edges connecting the nodes (keywords) depict an established relationship between the connected nodes. A thicker edge indicates a stronger association or closer relationship or high frequency of co-occurrence between the connected nodes. The thickness means more shared documents between the connected keywords, that is, the number of times the connected keywords co-occur in multiple documents. The thick edge connection between “scheduling” and “optimization” shows that the two keywords co-occur in more documents compared to other connected pairs of keywords. The importance of a keyword (node) within a network is shown by the number of links (edges) to that keyword. “scheduling” is an essential keyword with the highest betweenness centrality of 101.94. This means that the keyword forms the bridge between major research themes in this field (Painter et al., 2019).

The clusters are characterized by the areas of research in which these keywords are frequently co-occurring. The keywords in the blue cluster are closer to research areas such as packet scheduling and Long-Term Evolution, the green cluster cloud computing, green computing, fog computing, virtual machines, and big data, while the keywords in the red cluster often appear in CPU scheduling, parallel and distributed systems research.

4. Conclusion

This study conducted an exploratory bibliometric analysis of publications in Scheduling Algorithms research. The study results revealed that Scheduling algorithms related to research have an annual scientific production growth rate of 16.62%. The keyword “scheduling” is the most important keyword in scheduling algorithms research, with the highest betweenness centrality of 101.94. It forms the bridge between major research themes in Scheduling Algorithms related research. Edge Computing is the most discussed and trend topic concerning scheduling algorithms research in 2020 and 2021. Institutional collaborations have not been well-established in this field.

The limitation of this study is that the dataset used is from a single source; Scopus. This is because the biblioshiny interface does not have the facility to merge BibTeX files from different sources. Analysis of a combination of data from different sources such as Web of Science, Google Scholar, and Scopus may give better insight into the field. However, studies (Bar-Ilan, 2018; Martín-Martín et al., 2018, 2021) have shown that Scopus and Web of Science have most documents in common, that is, a large intersec of documents. According to Vieira and Gomes (2009), 2/3 of Scopus documents are available on the Web of Science. Ninety-three per cent of the documents found on the Web of Science are also in the Scopus database (Martín-Martín et al., 2021).

Future work may merge documents from different databases and filter out the duplicates. Although this study did not include preprints and articles in the press in its search string, such work may give a more accurate picture of the interests in this field. Also, it would be interesting to see the percentage of preprints in this field compared to refereed works. Future work could include preprints and articles in the press for these insights.

The findings of this study can help both budding and established researchers to find new research focus, relevant sources, and collaboration opportunities and make informed decisions as they research scheduling algorithms and their applications.

Declarations

Author contribution statement

Temidayo Oluwatosin Omotehinwa: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
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The authors declare no conflict of interest.

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