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Green scheduling to achieve green manufacturing: Pursuing a research agenda by mapping science

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A R T I C L E I N F O

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A B S T R A C T

The strengthening of measures to reduce greenhouse gas emissions meant that manufacturing scheduling had to acquire a green approach. The need to reduce energy consumption becomes necessary for companies to achieve sustainable development. Therefore, a new challenge for the scientific community was foreseen, researching new algorithms or knowledge hubs to achieve green scheduling. Green scheduling may be considered one of the principles of green manufacturing, aimed at minimizing environmental damage and energy waste. A review of the literature shows that there are no research works that analyze the scientific development carried out in "green scheduling" through methodologies based on bibliometric analysis, thus the need and the novelty of this research. Based on a dataset formed by 420 scientific documents published from 2006 to 2020 a bibliometric and network analysis is carried out to find the scientific trends, the main relationships according to collaborations and intermediaries, and the research hubs that help to establish the research agenda. The results show that "green scheduling" is a growing research area in the scientific community and in recent years the number of new research topics has experienced considerable growth. This research is developed in Asia, Europe and America, but China stands out as the most productive, collaborative, intermediary, influential and active country at present, through its organizations which are mainly universities, such as Huanzhong University of Science and Technology and Tongji University. However, research development related to green scheduling is carried out in a collaborative environment between institutions located in different countries, allowing countries that are not scientific powerhouses to develop research in the area. The network analysis makes it possible to define the research framework through the clustering of the dataset's research keywords, highlighting that the main areas of research focus on the development of new methods through algorithms aimed at improving energy efficiency in production environments, in areas of computational development such as cloud computing, and in transportation. The most cited research papers, considered the main drivers of knowledge, are published in high-quality research journals, and are mainly developments in scheduling algorithms for different work environments with a green approach. Research findings can provide the academic community with relevant information about green scheduling to make appropriate decisions and become a research agenda for future research.

1. Introduction

Industrial evolution has entrained excessive exploitation of resources without considering environmental deterioration. Concern about climate change has raised awareness among companies to reduce their carbon footprint [1]. This new perception has led to a change in the attitude of businesses in the production system, opening the way to environmentally conscious manufacturing [2]. Furthermore, the rising cost of energy has become another factor motivating initiatives to minimize energy consumption and GHG emissions in the industrial sector. In addition, in developed regions such as Europe and America, certain policies and regulations have been implemented that have been

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effective in launching green manufacturing systems [3].

In the 1990s the academic scientific community began to take an interest in the field of green manufacturing research; initially called "environmentally conscious manufacturing", then, around 1995 the synonymous term "green manufacturing" was defined [4]. Later, another term, namely "sustainable manufacturing" appeared, and United States Environmental Protection Agency [5] defined it as "Sustainable manufacturing is the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources. Sustainable manufacturing also enhances employee, community and product safety." This definition is based on the three pillars of sustainability, also known as the "triple-bottom-line", Environmental, Economic and Social dimensions.

2. Literature review

To achieve this sustainable production, manufacturing systems should reduce environmental impact and improve energy efficiency, provide work safety and improve personal health, among other things [6,7]. In this model of sustainability, Dornfeld et al. [8] define a model in which "green manufacturing" is considered to be designed for environmental sustainability, which in terms of application differs from "sustainable manufacturing". However, when green manufacturing is studied from an ecological environment viewpoint, social and economic benefits become important, which can lead to an overlap between the definitions of sustainable manufacturing and green manufacturing [9].

These different approaches have allowed Pang and Zhang [9] to define a green manufacturing system divided into application, organization and system - levels based on the analysis of scientific literature. The clustering process based on article keywords carried out in the research allows them to establish what they have called the principles of green manufacturing within the system-level, in which they group knowledge hubs relating to operational terms such as the "three Rs" of reuse, remanufacturing, and recycling defined by Sarkis and Rasheed [2], lean manufacturing and scheduling problems, among others. Also, research in this field requires mathematical methods to address problems that, with the help of computer science, are able to solve problems in scheduling [10,11]. This analysis allows several keywords related to energy (energy modeling, energy management, energy saving) to be identified, indicating that not only are pollution factors of key importance in the strategy to achieve green manufacturing but also energy savings. Reducing manufacturing energy consumption has mainly focused on developing more energy efficient machines and processes. However, focusing on this alone overlooks a major opportunity to be energy efficient. Compared to improvements in machine efficiency or process redesign, production scheduling has become a key element in achieving green production, playing an important role in reducing energy consumption [12–15].

Scheduling becomes a key issue for scientists to study. Therefore, the scientific community is now interested in developing new scheduling algorithms to reduce energy consumption, focusing not only on manufacturing but also on the data center industry, an energy-intensive industry that also aims at sustainability [16–18]. Scheduling with a green or sustainable goal becomes a challenge for the scientific community. Green scheduling is a major way to achieve sustainable industrial manufacturing [18] and enhance the green efficiency of enterprises looking for solutions concerning energy saving, minimization of energy consumption, carbon emission reduction [14,19–22]. Green scheduling may be considered one of the principles of green manufacturing, aimed at minimizing environmental damage and energy waste. The goals of green scheduling are based on the pillars of sustainability, achieving economic and environmental values founded on their objectives of reducing energy consumption, cost-savings and developing environmental-friendly modes [15,23–27]; and the social pillar by reducing the carbon footprint and developing scheduling algorithms that consider noise pollution; a common phenomenon in the manufacturing industry [28].

A fuller comprehension of the investigation carried out in green scheduling opens the doors to bibliometric techniques. Different from a literature review: the bibliometric technique provides an innovative and objective perspective through reliable quantitative processes, and has been widely used in scientific research as an analytical tool to help provide scholars with a general understanding of specific research areas and to assist researchers in the sorting of the domain literature [29,30]. In addition, bibliometric analysis becomes a tool that enables the geographic location of research, the identification of the main actors, the mapping of collaborative networks, and the identification of the research hubs, among others, which is of great help in defining a roadmap based on the research themes and prominent works in the select technological domain for the development of future research for the scientific community specialized in the area of interest [31,32]. In the main scientific databases, such as Web of Science and Scopus, the "green scheduling" research field has not been studied through bibliometric techniques. Nevertheless, Akbar and Irohara [7] carry out a review of scheduling for sustainable manufacturing that has served as a prelude to our research. This analysis is carried out from a very broad perspective such as the approach employing the dimensions of sustainability, based on the methodology of the research conducted by Gahm et al. [33], which carries out a review of literature on energy-efficient scheduling. However, other bibliometric analyses have been carried out in research fields related to industrial sustainability. Pang and Zhang [11] present a general cartography of existing research about green manufacturing and propose the architecture of the green manufacturing system and its links with the economic-social-eco system. Yin et al. [34] analyze global green innovation research trends from 1981 to 2016, offering a broad overview of trending publications, authors, countries, journals and identifying research hubs; a similar overview has been led by Albort-Morant et al. [35] identifying the research trend and interests in green innovation. As for green supply chain management, Fahimnia et al. [36], de Oliveira et al. [37], Gong et al. [38] and Tseng et al. [39] have carried out bibliometric analyzes in order to identify the most relevant research points, the behavior of the research field and future directions. Considering that green scheduling is a research hotspot in the field of job scheduling, Rossit et al. [40] present bibliometric analysis of the non-permutation flow-shop scheduling problem to show that the subject is an active research area.

Green scheduling is a fundamental process technique throughout green manufacturing. Thus, due to the drive to implement production systems that reduce the emission of polluting gases and therefore promote energy-efficient systems, the awareness of academic research to green scheduling has been growing in recent years. This concern has led to an increasing number of publications in this field, which is why a bibliometric analysis on the topic of green scheduling is proposed in this paper. The goal of this article is to map scientific research on green scheduling, answering the questions who, when, where and what is being investigated in order to have a better understanding of how scientific research is evolving, and thus be able to offer a research agenda to the scientific community that wants to do research in this area of knowledge.

3. Methodology

The methodological process followed to achieve the objective set out in this article is based on a bibliometric analysis of the scientific research carried out in recent years on green scheduling. The bibliometric method is approached in different ways depending on the authors, and is defined as a research method, or a research technique, that allows scientific literature, which represents extensive global data sets and reliable data [41–43] to be analyzed and measured quantitatively. In addition, in this article the bibliometric analysis is complemented by a network analysis. In this case, a bibliometric map of science (network) is defined as a visual representation of the quantitative relationships between textual or bibliographic units in a sample of scientific literature [44]. Moreover, the application of science mapping allows to verify the evolution of key topics related to green scheduling [45].

The overall procedure for analyzing the scientific trends, collaborations and research hotspots in green scheduling began with the selection of the primary search engine: the Scopus database. Scopus is one of largest curated abstract and citation databases of peer-reviewed literature (53 million documents indexed) [46,47]. Added to which, initial searches carried out with Scopus produced more results than with Web of Science (WoS). Therefore, Scopus was selected to provide scientific publications related to green scheduling (see Fig. 1).

In the next step, the identification of a proper query related to green scheduling (see Fig. 2) was necessary to ensure data accuracy. To this end, two main blocks were built: the unconditional set terms and the conditional set terms. In this way, high precision and high recall was achieved i.e., high accuracy (see Fig. 3). The query that is defined is included in the Scopus database search engine to obtain the study dataset, which will be analyzed in the next stage.

Unconditional set terms (block 1) filters data containing general green scheduling terms (green w/2 schedul*) and excludes terms (irrigation* or forest or "traffic light*" or "traffic signal*" or matroid or color) that lead to documents unrelated to the field of study, in title, abstract and keyword fields within concrete subject areas (computer science; energy; engineering; environmental science; mathematics; business management and accounting; and decision science). Consequently, the unconditional set, so-called seed, is obtained with high precision but perhaps low recall. Thus, almost all retrieved documents will be relevant, however, not all relevant documents are necessarily retrieved. Hence, the aim is to extend this set by retrieving potentially relevant documents and to filter those that are linked to the seed and so increasing recall without marring precision [48].

Conditional set terms (block 2) is obtained by filtering data containing other terms related to green scheduling terms ("green manufactur*" or "energy efficient schedul*" or "green production*") in title, abstract and keyword fields within concrete subject areas (computer science; energy; engineering; environmental science; mathematics; business management and accounting; and decision science) within the citing documents obtained from the unconditional set. This block will allow us to improve the search results by including articles related to green scheduling that were not identified in the previous block, including terms related to green production and energy efficiency, defined after a review of the main keywords used in the scientific literature related to green scheduling.

Finally, once repeated documents have been eliminated, the conditional set is merged with the unconditional set into the final selection of relevant publications, and in this way the final set is obtained with high precision and high recall, i.e., with high accuracy [49]. This phase ends by generating the dataset formed by scientific publications that meet the requirements of the query, and in turn with the objectives of the research.

Subsequently, the dataset generated in the previous phase is imported into the Vantage Point (VP) software [51], through which the raw data can be classified and the data cleaned thanks to the use of fuzzy matching techniques, grouping terms with identical meaning. In addition, VP integrates techniques for analyzing the dataset, such as, factor analysis, co-occurrence and correlational analysis of fields, Principal Component Analysis (PCA), natural language programming, Social Network Analysis (SNA), clustering processes, and other capabilities for analyzing or mapping data.

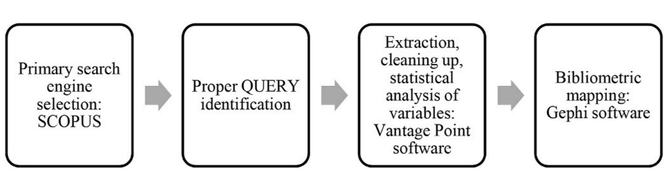

Fig. 1. Workflow of the bibliometric analysis model.

Once the dataset has been cleaned up, the analysis of the co-occurrence matrices will allow us to initialize the collaboration networks of the dataset. The process of generating, visualizing and analyzing the networks will be carried out through the Gephi software [52]. The use of these techniques for bibliometric analysis has allowed us to map and analyze the collaboration networks between countries and organizations, the main areas of knowledge and those that are developed by the leading organizations, identify the main publishers, as well as identify and analyze the main drivers of knowledge. In addition, a co-citation analysis will allow us to identify the main references that are feeding the most cited publications, and their relationships.

The study period is set from year 2006–2020, and after removing irrelevant publications, 420 publications were obtained for bibliometric and network analysis.

4. Results

4.1. The number of publications and their citations

The number of publications and citations per year is presented in Fig. 4. The number of publications since 2010 has been growing gradually, but the number of citations of these publications has increased sharply, indicating growing academic interest in green scheduling, especially in the last five years. The first publication is from 2006, but there are hardly any publications until 2010; surely due to a certain indifference towards green or sustainable manufacturing scientific production [11]. However, the number of publications and citations rapidly increased from 2010. The number of publications published in 2020 is almost seven times greater than in 2010. Likewise, the number of citations per year for publications in 2020 was over one hundred and twenty-eight times higher than in 2010. The main reason is that the science research community is paying more attention to such a topic related to sustainability in the manufacturing environment.

4.2. Who is researching? Academic landscape

In order to identify the leading work hubs in the scientific development of scheduling, applied in a green environment, the main countries and organizations are analyzed. For this purpose, on the one hand, the main producers are identified, and on the other hand, the collaboration networks are analyzed in order to identify the collaboration groups and the key figures according to their intermediation or influence on the rest.

In total, authors from 55 countries published their papers on green scheduling. China is the most productive country with 181 publications, accounting for 43% of total publications, followed by USA (16.42%). Other productive countries include several Asian-Pacific and European countries and Canada, so the research topic is well spread over the world. In addition, it is important to ascertain the degree of scientific collaboration of the countries, for this reason, the method of network analysis, based on the co-occurrence matrix, allows us to identify the most collaborative, the most influential and the main intermediary countries (see Table 1).

China and the USA lead in all the network characteristics analyzed, being the most collaborative, most influential, most collaborative, most influential and most intermediary countries. However, two European countries, France and the UK, are also relevant in these relationships, as are Australia and Canada. It is noteworthy that certain countries with little scientific production (Spain, Pakistan …) have a good position in terms of their capacity to be intermediaries or influencers, which indicates that their development is always done in international collaboration. Using Gephi for network analysis, main countries (countries that have at least one collaboration) with international collaboration were identified and plotted (see Fig. 5). The size of the node represents the

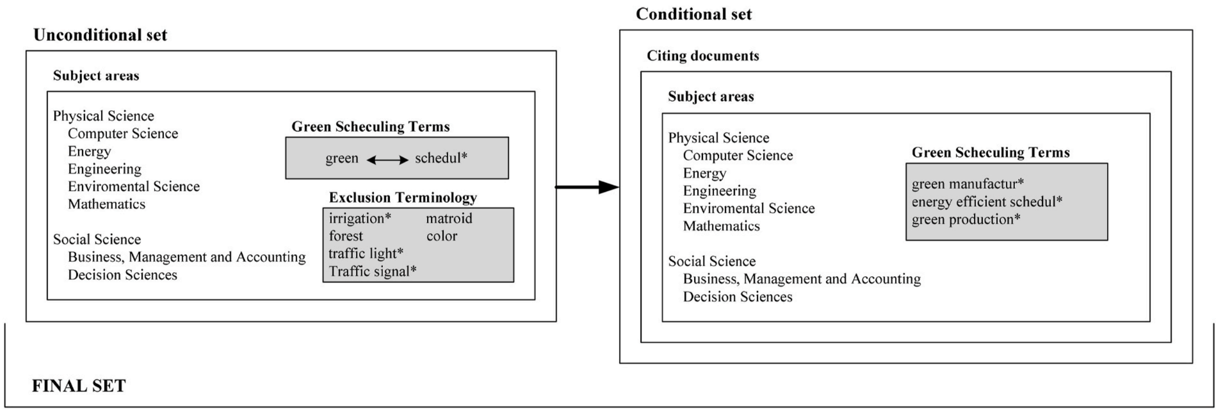

Fig. 2. Main terminology related to green scheduling. Note: Words with asterisk (*) are root words, i.e., these words plus all possible suffixes are contemplated in the query.

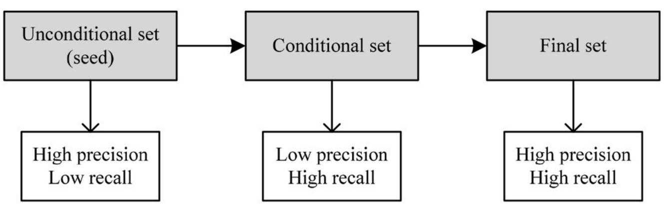

Fig. 3. Unconditional and conditional set terms for obtaining final set terms. Source [50].

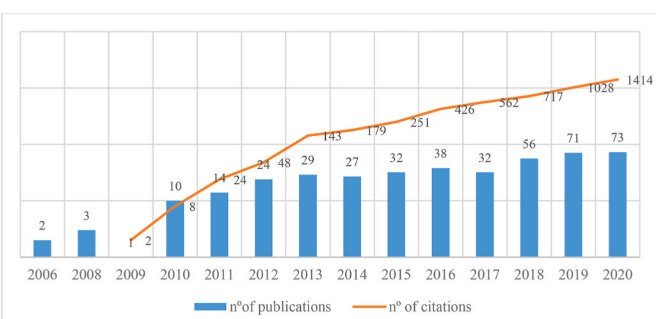

Fig. 4. General trends of publications and citations from 2006 to 2020.

total publications in collaboration of one country, so a country with a larger node is more active in collaborations related to the field of green scheduling, such as China and USA. The width of the connecting line represents the cooperative frequency with other country, therefore, the academic collaboration between China and USA is the most frequent. Nevertheless, both of them collaborate with European and Asian-Pacific countries, such as France, UK, Japan, Turkey, South Korea, India, among others. Scientific development is located in Europe, America and Asia-Pacific, highlighting that, in terms of collaboration, the scientific powers are located in the central positions of the network and are surrounded by emerging countries seeking their place in the development

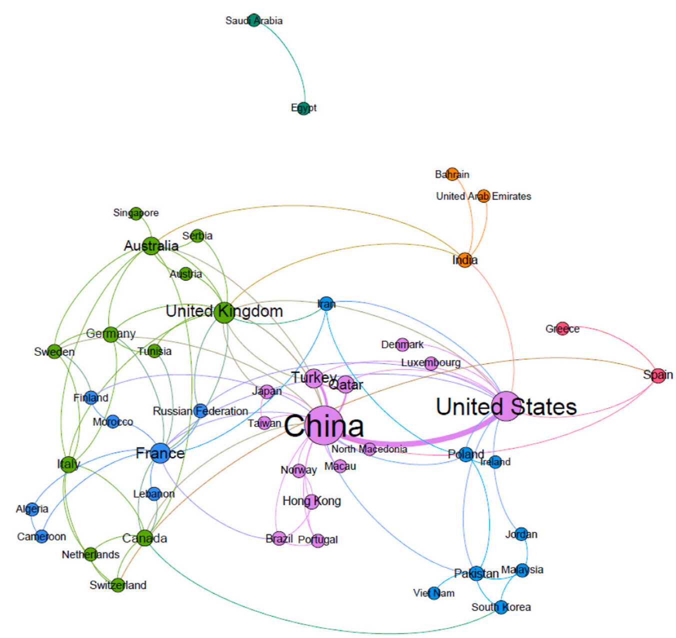

Fig. 5. Academic collaboration among main countries.

Table 1
Ranking of the most productive, collaborative, intermediary, and influential countries.

Ranked	Countries most productive	Number of Publications	Countries most collaborative	Weighted Degree	Intermediary countries	Betweenness centrality	Influential countries	Closeness centrality
1	China	181	China	68.0	China	414,59	China	0.625
2	United States	69	United States	44.0	United States	239,96	United States	0.57
3	India	49	United Kingdom	22.0	France	189,07	United Kingdom	0.555
4	France	34	France	20.0	United Kingdom	153,62	France	0.535
5	United Kingdom	26	Turkey	17.0	Australia	104,50	Australia	0.5
6	Canada	14	Australia	14.0	Canada	91,20	Canada	0.5
7	Iran	14	Qatar	13.0	India	89,66	Pakistan	0.454
8	Australia	13	Canada	10.0	Pakistan	85,33	Poland	0.45
9	Turkey	13	Italy	10.0	Spain	58,36	Sweden	0.45
10	Japan	9	Germany	8.0	Poland	47,59	Turkey	0.45

of this research field. Possible reasons for collaborations may include English, science capability proximity, international students, among others [53]. Furthermore, as is shown in Fig. 5, India, despite being the third country with the most publications, does not have a high degree of collaboration in the process of developing such publications, the same is true with Iran and Japan.

Regarding organizations, Table 2 lists the top 10 active academic organizations, including their affiliated countries, and the publications and the citations of their publications. Huazhong University of Science and Technology is the most productive institution with 21 publications, followed by Tsingua University (12 publications) and Ludong University and the University of Pennsylvania with 10 publications. However, average citations per publication for the University of Pennsylvania (ranked#4) is similar to the average of the Huazhong University of Science and Technology (ranked#1). In general, Chinese organizations that ranked among the best in terms of productivity have a similar average number of citations, with the exception of Shandong University, which has a very low average. It should be noted that this organization's research on green scheduling is very recent.

The network analysis has allowed us to identify the main collaborations. The network obtained has a high modularity (0.896), which is related to a high clustering or interrelated groups. Fig. 6 shows the collaborations that have a value of the weighted degree parameter (node size) higher than 5, which indicates the minimum number of collaborations that the organizations represented have. In addition, part a) of the figure shows the clustering of the network, with the different collaboration groups indicated by color. In part b) of Fig. 6, the collaboration network is represented by the color of the node indicating the degree of intermediarity or betweeness centrality, allowing us to identify the organizations with the greatest intermediary capacity (the darkest nodes). The analysis of the network identifies Huazhong University of Science and Technology as the most collaborative organization with the greatest intermediary capacity. Table 3 shows the numerical value of the main relationships between organizations.

Among the most productive universities, Tongji University stands out for its ability to be an intermediary and influencer in the collaborative development of green scheduling research. In addition, the IBISC laboratory of the University of Évry (France) is a reference in terms of collaboration with other national and international universities, although it is not among the most productive.

4.3. *What topics are being researched?*

The identification of the main research topics and their research fields facilitates the definition of the research agenda linked to green scheduling. For this purpose, on the one hand, the scientific evolution of the research environment is identified by analyzing the number of keywords generated each year, and, on the other hand, the network generated is analyzed based on the matrix of co-occurrences of the keywords that represent the knowledge hubs of academic studies. A total of 987 author's keywords were extracted from 420 publications by using VP.

Table 2
The most productive organizations.

Ranked	Affiliation	Publications	Country	Average citations per publication
1	Huazhong University of Science and Technology	21	China	16.71
2	Tsinghua University	12	China	13.58
3	Ludong University	10	China	8.4
4	University of Pennsylvania	10	USA	15.3
5	Harbin Institute of Technology	9	China	9.12
6	Shandong University	8	China	0.66
7	Shanghai Jiao Tong University	8	China	11.5
8	Tongji University	8	China	10.87
9	Yasar University	8	Turkey	3.37
10	Qatar University	7	Qatar	2.85

As shown in Fig. 7, the definition of new topics has two periods of high growth, 2012–2013 and 2015–219, which suggests that the research area related to green scheduling is in a phase of growth and expansion to new scientific developments. That said, what are the main research fields? The network analysis will allow us to identify them and give a new vision to the scientific community of the main subgroups that will enable them to correctly direct future research.

Fig. 8 shows the network of co-occurrences of keywords whose nodes have at least 12 co-occurrences. These nodes represent the most relevant topics in the study; the larger the size of the node the more often it has been defined as a topic in the study dataset that is limited to the green scheduling research topic. Therefore, the most important topics are Energy Efficiency, Scheduling, Cloud Computing, Green Scheduling and Multi-objective Optimization. In addition, these nodes will mark the modularity or clustering of the network and, in turn, as shown in Table 4, these topics top the ranking of the most influential and most intermediary research topics.

Once the main research topics have been identified, the analysis of the clusters will allow us to identify the most specific research environments or fields linked to these main topics. In the analysis of Fig. 8, the following four main clusters are identified, grouping 53.43% of the keywords. The first cluster (pink) covers 17.71% of the keywords and is led by two topics related to energy improvement and optimization of production system scheduling, namely Energy-efficient scheduling and Multi-objective optimization. The main terms associated with the group are: genetic algorithm, hybrid flow-shop scheduling, sustainable manufacturing, sequence-dependent setup time, parallel machine, green manufacturing or production, job shop scheduling, makespan and mixed integer linear programming. The second most important cluster gathers 15.66% of the terms (green), and is headed by the terms Cloud computing and Green scheduling. The research field covered by this cluster is focused on data management in scheduling with a sustainable approach: Data center, green cloud, virtual machine, task scheduling, carbon emission, renewable energy and dynamic voltage and frequency scaling (DVFS). The third cluster (blue) groups 13.1% of the keywords, and it is the most co-occurring terms that lead the grouping, Energy Efficiency and Scheduling, which in turn are related to all the clusters formed in the network. Therefore, the research field that marks this cluster is not very specific and is made up of keywords from different fields, such as: green computing, green communications, orthogonal frequency-division multiple access (OFDMA), heuristics, batch processing, grid, energy, resource scheduling. The fourth (red), grouping only 6.96% of the terms, is led by Energy consumption. The topics of this cluster are also related to production systems: flexible job shop scheduling, load balancing, reliability, batch scheduling, low-carbon production scheduling and multi-objective. Finally, the next cluster (orange) is linked to green transportation, although it is a very small grouping.

In order to obtain a more practical result on the research topics, Table 5 shows a classification of the different clusters formed according to the dimensions considered appropriate, based on the methodology used in the review on scheduling in sustainable manufacturing carried out by Akbar and Irohara [7].

Having identified the main research fields in the study area, it is interesting to identify which of these topics are being researched in the most productive universities in recent years. Considering the recentness as the years 2019–2020, the most productive organizations are: Huazhong University of Science and Technology (12 publications), Shanghai University (7 publications), Ludong University, Yasar University (Turkey), Tsinghua University, Henan Institute of Technology and Qatar University (Qatar) with 6 publications. As shown in Fig. 9, Huanzhong

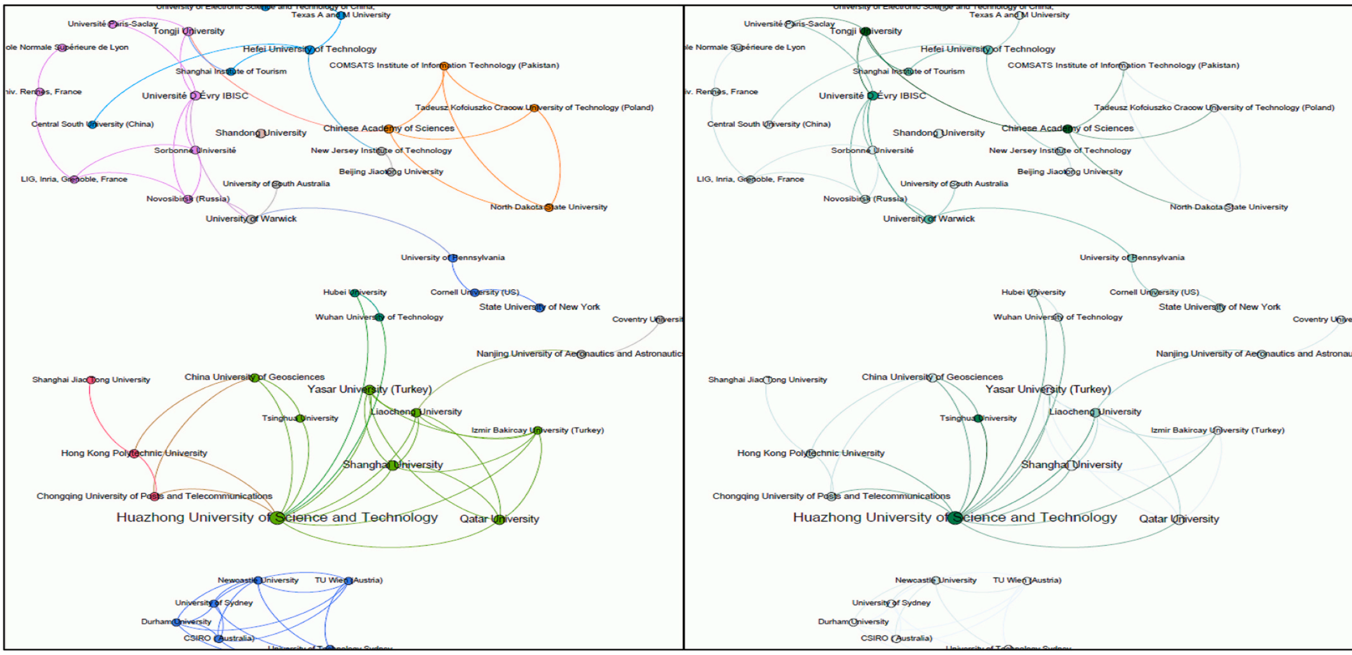

Fig. 6. Academic collaboration among organizations: a) collaborations by modularity b) collaborations by betweeness centrality.

Table 3
Ranking of the most collaborative, intermediary, and influential Organizations.

Ranked	Organizations most collaborative	Weighted Degree	Intermediary organizations	Betweenness centrality	Influential organizations	Closeness centrality
1	Huazhong University of Science and Technology	38.0	Tongji University	9.135,16	Tongji University	0.2919
2	Shanghai University	19.0	Chinese Academy of Sciences	8774.0	Chinese Academy of Sciences	0.2856
3	Qatar University	18.0	Huazhong University of Science and Technology	7.625,16	Université D Évry IBISC	0.2840
4	Yasar University (Turkey)	18.0	Tsinghua University	7476.0	Tsinghua University	0.2683
5	Université D Évry IBISC	13.0	Université D Évry IBISC	5.961,99	Shanghai Institute of Tourism	0.2505
6	Hefei University of Technology	12.0	University of Warwick	4.268,33	Université Paris-Saclay	0.2492
7	Liaocheng University	12.0	Shanghai Institute of Tourism	3.732,66	Huazhong University of Science and Technology	0.3213
8	Shandong University	12.0	Hefei University of Technology	3.618,10	University of Warwick	0.2657
9	Tongji University	11.0	Liaocheng University	3.072,30	COMSATS Institute of Information Technology (Pakistan)	0.2355
10	Chinese Academy of Sciences	11.0	University of Pennsylvania	2877.0	China University of Geosciences	0.2633

and Shanghai University base their research on topics related to: hybrid flow shop scheduling, no-idle flow shop scheduling, multi-objective optimization, energy-efficient scheduling, heuristic optimization, meta-heuristic, genetic algorithm, sequence-dependent setup time. Ludong University and Henan focus research on: energy consumption, whale optimization algorithm, low carbon production scheduling, flexible job shop scheduling, non linear convergence factor, mutation operation, dispatching rule. Tsinghua University focuses on total energy consumption (TEC), sequence-dependent setup time, green scheduling, energy efficiency, hybrid flow shop scheduling, decomposition. Finally, Qatar University and Yasar University also do research in very similar areas such as: bi-objective and multi-objective optimization, heuristic optimization, permutation flow shop scheduling, no-idle flow shop scheduling, no wait permutation flow shop scheduling, distributed job shop problem and meta-heuristic ensemble.

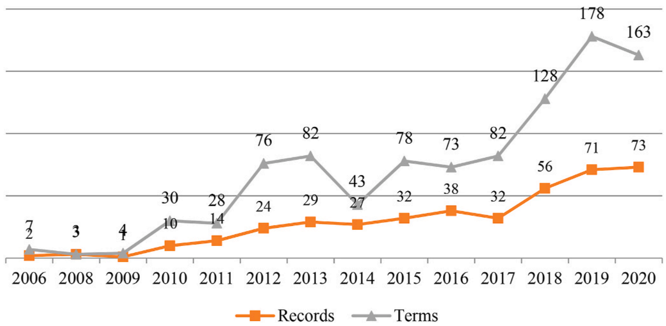

Fig. 7. Number of publications vs new author's keywords by year.

4.4. Who is publishing? Main journals and subject areas

According to Scopus, the publications can be categorized into four general subject areas, which are classified into a total of thirty more specific areas. The related publications are categorized into a total of fifteen specific areas, nonetheless, the following areas can be considered as the most relevant: Computer science (70% of the total of publications), Engineering (55%), Mathematics (20%), Business, management and accounting (13%), Environmental science (11%), Energy (11%) and Decision Science (9%). In general, the publication of research related to green scheduling is oriented towards the physical science area.

The most productive journal is closely related to sustainability production, however, most of the top journals are related to computer science. The 420 publications were published in 261 different sources; therefore the works are not centered on a few journals. Table 6 provides an overview of the 10 most productive journals in research related to

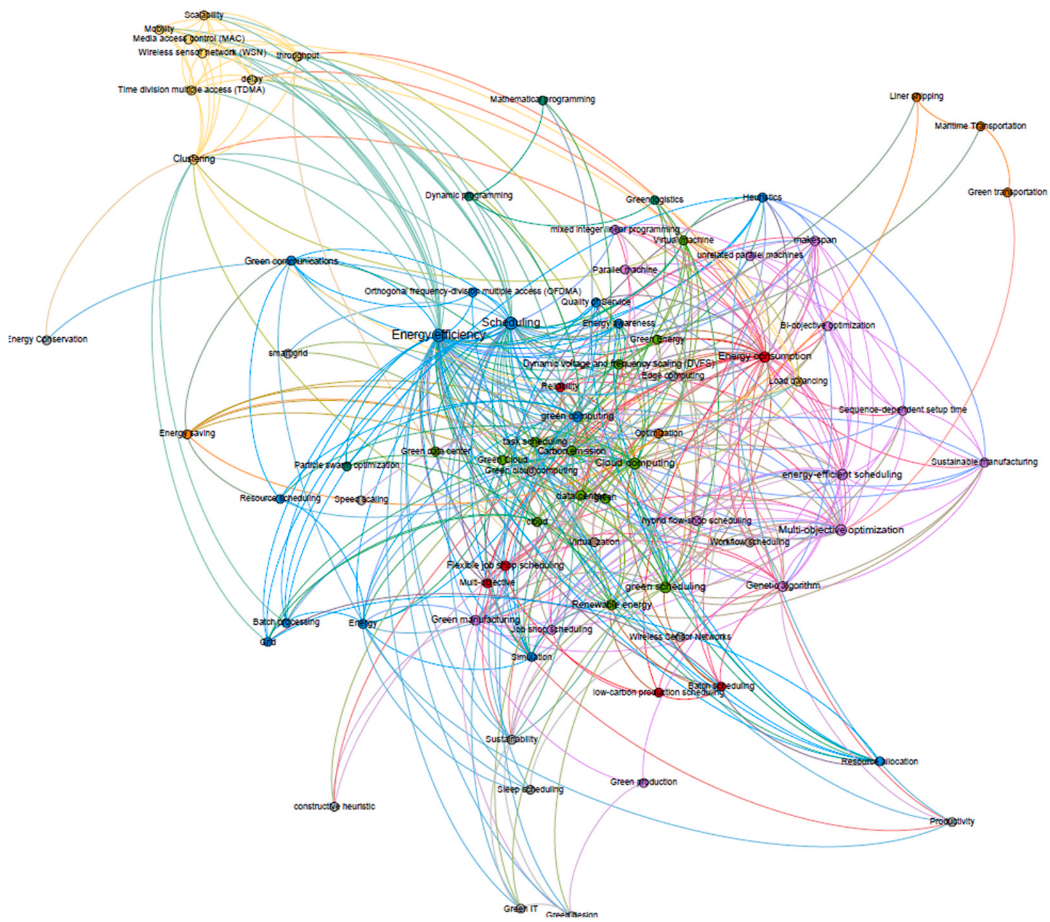

Fig. 8. Author's keywords co-occurrences network.

Table 4
Ranking of the most co-occurring, intermediary, and influential keywords.

Ranked	Keywords	Weighted Degree	Intermediary keywords	Betweenness centrality	Influential keywords	Closeness centrality
1	Energy efficiency	261.0	Scheduling	88208.12	Energy efficiency	0.5008
2	Scheduling	232.0	Energy efficiency	85253.03	Scheduling	0.4958
3	Cloud computing	148.0	Green scheduling	53417.88	Cloud computing	0.4762
4	green scheduling	144.0	Energy consumption	36328.78	Energy consumption	0.4690
5	Multi-objective optimization	132.0	Multi-objective optimization	35633.28	Multi-objective optimization	0.4680
6	Energy consumption	122.0	Cloud computing	33036.95	Green scheduling	0.4524
7	Energy-efficient scheduling	110	Energy-efficient scheduling	30816.15	Data center	0.4485
8	Data center	93.0	Green computing	23505.04	Green computing	0.4426
9	Green computing	90.0	Green manufacturing	21965.50	Genetic algorithm	0.4346
10	Renewable energy	72.0	Renewable energy	17585.24	Renewable energy	0.4324

Table 5
The research framework based on the clustering process of the keyword network.

	Application or purpose	Objective Function	Manufacturing model	Model type	System of objectives	Solution Method
Cluster 1	✓ Sustainable or green manufacturing ✓ Optimization ✓ Energy-efficient scheduling	✓ Minimize makespan (economic-oriented objective) ✓ Minimize energy consumption (environmental-oriented objective)	✓ Hybrid flow-shop ✓ Parallel machine ✓ Job shop	✓ Mixed Integer linear programming	✓ Multi-objective ✓ Bi-objective	✓ Sequence-dependent setup time ✓ Genetic algorithm
Cluster 2	✓ Cloud computing ✓ Green scheduling ✓ Renewable Energy	✓ Minimize carbon emissions (environmental-oriented objective)	✓ Data center	✓ Task scheduling		✓ DVFS ✓ Virtual Machine
Cluster 3	✓ Energy Efficiency ✓ Scheduling	✓ Minimize makespan (economic-oriented objective) ✓ Minimize energy consumption (environmental-oriented objective)	✓ Green communications ✓ Batch processing ✓ Green computing	✓ Grid		✓ OFDMA ✓ Heuristic ✓ Simulation
Cluster 4	✓ Energy comsumption ✓ Low-carbon production	✓ Minimize energy consumption (environmental-oriented objective)	✓ Flexible job shop ✓ Batch scheduling	✓ Based on Reliability of systems	✓ Multi-objective	✓ Load balancing
Cluster 5	✓ Green transportation ✓ Optimization	✓ Minimize energy consumption (environmental-oriented objective)	✓ Maritime transportation	✓ Liner shipping	✓ Multi-objective	

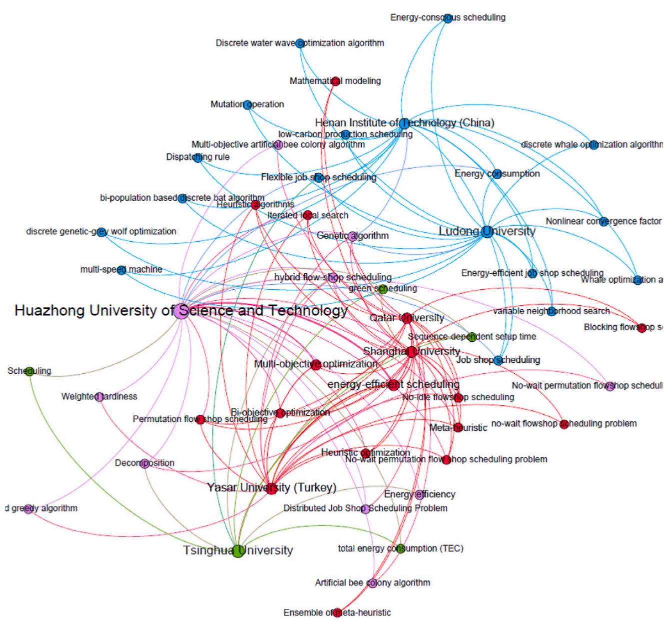

Fig. 9. Most productive organizations during 2019–2020 and author's keyword co-occurrence network.

green scheduling, including the publisher, the number of publications, as well as the Journal Citation Report and Scientific Journal Ranking analysis. Journal of Cleaner Production is the most prolific journal in green scheduling with 20 publications. The second most productive journal is IEEE Access and Lecture Notes in Computer Science (14 publications). Elsevier, one of the world's most renowned academic publishing companies, has an important role in the top publishers. However, the presence of IEEE stands out at the top, whose scientific expression is closely linked to technical developments, which indicates that the research related to this publisher has a practical purpose. In addition, the journals with the highest number of publications are classified in their categories in the first quartile, which indicates that a significant number of publications, specifically 23% of the total, are of high research quality.

4.5. Main knowledge drivers: a priori and a posteriori key knowledge

In order to carry out a more exhaustive review of the green scheduling theme developed by the scientific community, it was decided to analyze manually the publications with the highest number of citations, since they can be defined as the key resources in the dissemination of knowledge in this area of research. In this case, the 10 most cited publications account for 1487 of the 2991 citations of all the documents in this search. This means that around 4% of the documents account for around 50% of the total citations. The identification of the most cited publications, in addition to identifying the main actors and main research topics that are having the greatest impact on a posteriori developed investigations, is a good indicator of how often they will be cited in the near future [54]. Thus, these publications become a reference for future research.

As is shown in Table 7, seven of the ten most cited documents [55–61] concern scheduling algorithms applied in different environments. Two other documents [62,63], which are among the most cited, develop schedulers for datacenters and Networked Fog Centers (NetFCs). And Mansouri et al. [64] introduce energy consumption as a criterion in scheduling a sustainable manufacturing environment. All these documents are defined within the subject area of Computer Science and Engineering. As far as the source of these documents is concerned, it is very variable, so no one source of information has more repercussion than another in the expansion of this research field. The sources of the most cited articles are mainly journals, with the exception of two conference proceedings. Furthermore, with the exception of Morocco and Taiwan, eight of the 10 most cited publications originate from the ten countries with the highest number of publications. Moreover, four of the most cited publications have been produced through academic collaborations. In addition, no document that reviews scientific performance related to green scheduling has been found.

But are these publications becoming a reference for research related to green scheduling? A citation analysis allows us to determine the knowledge return of these publications. A citation analysis is a bibliometric technique that allows us to investigate the relationships between citations. The three types of citations are direct citations, bibliographic coupling and co-citation [67]. In this case, we are interested in knowing which references are being used in more than one publication in our dataset, specifically in the most cited publications, using the bibliographic coupling method defined by Kessler [68]. The more references two documents have in common, the more they are related. In addition, if we want to identify which of these most cited articles are the source of knowledge for other publications in our dataset, the co-citation method proposed by Small [69] is used. In this way, we identify which relationships are most influential in knowledge transfer, and we can identify the main research topics that are feeding the scientific development of green scheduling. To carry out this analysis, a network has been generated from the table of co-occurrences of the most cited publications (those that have been cited up to 48 times have been

Table 6
The 10 most productive journals.

Journal name	Publisher	Publications (rank)	JCR			SJR		
			Field of research	Quartile	Impact factor 2019	Field of research	Quartile	Impact factor 2019
Journal of Cleaner Production	Elsevier BV	20 (1)	Engineering, Environmental	Q1	7.246	Environmental Science (miscellaneous)	Q1	1.886
			Environmental Sciences	Q1		Industrial and Manufacturing Engineering	Q1	
			Green & Sustainable Science & Technology	Q1		Renewable Energy, Sustainability and the Environment	Q1	
						Strategy and Management	Q1	
						Theoretical Computer Science	Q3	
IEEE Access	IEEE	14 (2)	Computer Science, Information Systems	Q1	3.745	Computer Science (miscellaneous)	Q1	0.775
			Engineering, Electrical & Electronic	Q1		Engineering (miscellaneous)	Q1	
			Telecommunications	Q1		Materials Science (miscellaneous)	Q2	
Lecture Notes in Computer Science	Springer Verlag	14 (3)	Computer Science, Theory & Methods	Q4	0.402 (2005)	Computer Science (miscellaneous)	Q2	0.427
Computers And Industrial Engineering	Elsevier Ltd.	7 (4)	Computer Science, Interdisciplinary Applications	Q1	4.135	Computer Science (miscellaneous)	Q1	1.469
			Engineering, Industrial	Q1		Engineering (miscellaneous)	Q1	
IEEE International Conference on Communications	IEEE	7 (5)	–	–	–	–	–	–
International Journal of Production Research	Taylor & Francis	7 (6)	Engineering, Industrial	Q1	4.577	Industrial and Manufacturing Engineering	Q1	1.776
			Engineering, Manufacturing	Q1		Management Science and Operation Research	Q1	
			Operations Research & Management Science	Q1		Strategy and Management	Q1	
Sustainable Computing Informatics and Systems	Elsevier USA	7 (7)	Computer Science, Hardware & Architecture	Q2	2.798	Computer Science (miscellaneous)	Q2	0.473
			Computer Science, Information Systems	Q2		Electrical and Electronic Engineering	Q2	
IEEE Transactions on Vehicular Technology	IEEE	6 (8)	Engineering, Electrical & Electronic	Q1	5.379	Aerospace Engineering	Q1	1.634
			Telecommunications	Q1		Applied Mathematics	Q1	
						Automotive Engineering	Q1	
			Transportation Science & Technology	Q1		Computer Networks and Communications	Q1	
						Electrical and Electronic Engineering	Q1	
Cluster Computing	Baltzer Science Publishers BV	5 (9)	Computer Science, Information Systems	Q2	3.458	Computer Networks and Communications	Q2	0.412
			Computer Science, Theory & Methods	Q1		Software	Q2	
Future Generation Computer Systems	Elsevier BV	5 (10)	Computer Science, Theory & Methods	Q1	6.125	Computer Networks and Communications	Q1	1.216

considered) and their references. The analysis of this network (see Fig. 10) has allowed us to do the co-citation analysis, identifying those among the most cited publications that become a bibliographic source for other most cited publications and those references that are the most shared as a source of knowledge by the top cited publications through the analysis of the network's betweeness centrality parameter. The blue titles are those publications of our dataset most cited, the red titles are those references with a higher degree of betweenness, the light green titles are those publications most cited that are references of other top references, and the dark green titles are other references but with a lower degree of sharing.

The co-citation analysis is described in Table 8, which specifies the main relationships between the most cited publications and the references with the highest degree of intermediarity. In addition, those references that are presented in the greatest number of publications are underlined, but in general the summary shows those that have the greatest diffusion among the most cited publication from de research dataset. The last two references are publications of the obtained dataset, which are references to other documents of the dataset. For example, it is worth highlighting how important the source of knowledge from the work done by Mansouri, Aktas and Besikci (2016) is for other research.

In order to identify the research topics and the organizations developing this research from the cited bibliographic references identified in the network of Fig. 10, an analysis of the generated network is performed based on the matrix of co-occurrences of their keywords and affiliations (see Fig. 11). As far as the research topics are concerned, the keyword network presents clustering groups that represent different approaches to the application of the research models linked to scheduling: manufacturing model (flow shop, job shop, …), model type (linear programming, integer programming, …), system objectives, solution

Table 7
The 10 most cited publications.

Cited by	Document title	Year	Authors	Affiliation	Country	Subject area	Source	Author keywords	Purpose/achievement
263	Directional routing and scheduling for green vehicular delay tolerant networks [55]	2013	Zeng, Y. Xiang, K. Li, D. Vasilakos, A.V.	Wuhan University Hubei University of Economics Wuhan University University of Western Macedonia	China China China Macedonia	Computer Sciences, Engineering	Wireless Network	DTN; Vehicular networks; Energy–efficient; Opportunistic routing; Scheduling	"Directional routing and scheduling scheme (DRSS) **algorithms** for green vehicle DTNs by using Nash Q-learning approach"
223	Energy-Efficient Adaptive Resource Management for Real-Time Vehicular Cloud Services [62]	2019	Shojafar, M. Cordeschi, N. Baccarelli, E.	Sapienza University of Rome Sapienza University of Rome Sapienza University of Rome	Italy Italy Italy	Computer Sciences	IEEE Transactions on Cloud Computing	TCP/IP-based vehicular cloud computing; Cognitive computing; Virtualized fog centers; Adaptive resource management; Energy-efficiency	"They propose and test an energy-efficient adaptive resource scheduler for Networked Fog Centers (NetFCs) "
198	A green energy-efficient scheduling algorithm using the DVFS technique for cloud datacenters [56]	2014	Wu, C.-M. Chang, R.-S. Chan, H.-Y	National Dong Hwa University National Dong Hwa University National Dong Hwa University	Taiwan Taiwan Taiwan	Computer Science	Future Generation Computer Systems	Cloud computing; Scheduling algorithm; Dynamic voltage frequency scaling; Datacenters	"Provide a green energy-efficient scheduling algorithm using the Dynamic Voltage Frequency Scaling (DVFS) technique for cloud computing datacenters"
161	GreenSlot: Scheduling energy consumption in green datacenters [65]	2011	Goiri, Í. Le, K. Haque, M. E. Beauchea, R. Nguyen T. D. Guitart, J. Torres, J. Bianchini, R.	UPC/BSC/ Rutgers University Rutgers University Rutgers University Rutgers University Rutgers University UPC/BSC UPC/BSC Rutgers University	United States United States United States United States United States Spain Spain United States	Computer Science	Proceedings of 2011 SC - International Conference for High Performance Computing, Networking, Storage and Analysis	Green energy; Energy-aware job scheduling; Datacenters	"Propose GreenSlot, a parallel batch job scheduler for a datacenter powered by a photovoltaic solar array and the electrical grid (as a backup)"
154	Performance evaluation of a green scheduling algorithm for energy savings in cloud computing [57]	2010	Duy, T.V.T. Sato, Y. Inoguchi, Y.	Japan Advanced Institute of Science and Technology Japan Advanced Institute of Science and Technology Japan Advanced Institute of Science and Technology	Japan Japan Japan	Computer Science, Mathematics	Proceedings of the 2010 IEEE International Symposium on Parallel and Distributed Processing, Workshops and Phd Forum, IPDPSW 2010	Energy savings; Green scheduling; Neural predictor; Cloud computing; Datacenters	"Design, implement and evaluate a green scheduling algorithm integrating a neural network predictor for optimizing server power consumption in cloud computing"
148	Green scheduling of a two-machine flowshop: Trade-off between	2016	Mansouri, S.A. Aktas, E.	Brunel University London	United Kingdom	Computer Sciences, Decision Sciences, Mathematics	European Journal of Operational Research	Green scheduling; Sustainable manufacturing; Multi-objective	"Incorporate the **energy consumption** as an explicit **criterion in shop floor scheduling**, in order to introduce

(*continued on next page*)

Table 7 (*continued*)

Cited by	Document title	Year	Authors	Affiliation	Country	Subject area	Source	Author keywords	Purpose/achievement
	makespan and energy consumption [64]		 Besikci, U.	Cranfield University SabreTurkey	United Kingdom Turkey			optimization; Sequence-dependent setup times	sustainability considerations in manufacturing scheduling"
91	An energy-efficient multi-objective optimization for flexible job-shop scheduling problem [59]	2017	Mokhtari, H. Hasani, A.	Faculty of Engineering, University of Kashan Shahrood University of Science and Technology	Iran Iran	Chemical Engineering, Computer Science	Computers and Chemical Engineering	Energy consumption; Energy-efficient scheduling; Industrial processes; Scheduling problems; Multi-Objective optimization	"**Design an energy-efficient scheduling** in a shop floor industrial environment, i.e., flexible Job-Shop Scheduling Problem (FJSP), and to this end, **a multi-objective optimization model** is developed"
87	A shuffled frog-leaping algorithm for flexible job shop scheduling with the consideration of energy consumption [60]	2017	Lei, D. Zheng, Y. Guo, X.	Wuhan University of Technology Hubei University Southwest Jiaotong University	China China China	Business Management and Accounting, Decision Sciences, Engineering	International Journal of Production Research	Flexible job shop; Scheduling; Shuffled frog-leaping algorithm; Total energy consumption; Workload balance	"Analyze Flexible Job Shop Scheduling Problem (FJSP) with the minimization of workload balance and total energy consumption, and the conflicting between two objectives. A **Shuffled Frog-Leaping Algorithm** (SFLA) is proposed based on a three-string coding approach"
83	A green strategic activity scheduling for UAV networks: A sub-modular game perspective [58]	2016	Koulali, S. Sabir, E. Taleb, T. Azizi, M.	Mohammed First University of Oujda Hassan II University of Casablanca Sejong University/Aalto University Mohammed First University of Oujda	Morocco Morocco Finland Morocco	Computer Sciences, Engineering	IEEE Communications Magazine	Scheduling, wireless telecommunications networks, energy efficiency (indexed keywords)	"**focus on the scheduling of beaconing** periods as an efficient means of energy consumption optimization, they provide **a learning algorithm** that ensures convergence of the considered Unmanned Aerial Vehicle (UAV) network with its unique Nash equilibrium operating point"
79	A green train scheduling model and fuzzy multi-objective optimization algorithm [66]	2013	Li, X. Wang, D. Li, K. Gao, Z.	Beijing Jiaotong University Beijing Jiaotong University Beijing Jiaotong University Beijing Jiaotong University	China China China China	Mathematics	Applied Mathematical Modeling	Train scheduling; Energy consumption; Carbon emission; Fuzzy multi-objective optimization	"Propose a **multi-objective train scheduling model** by minimizing the energy and carbon emission cost as well as the total passenger-time"

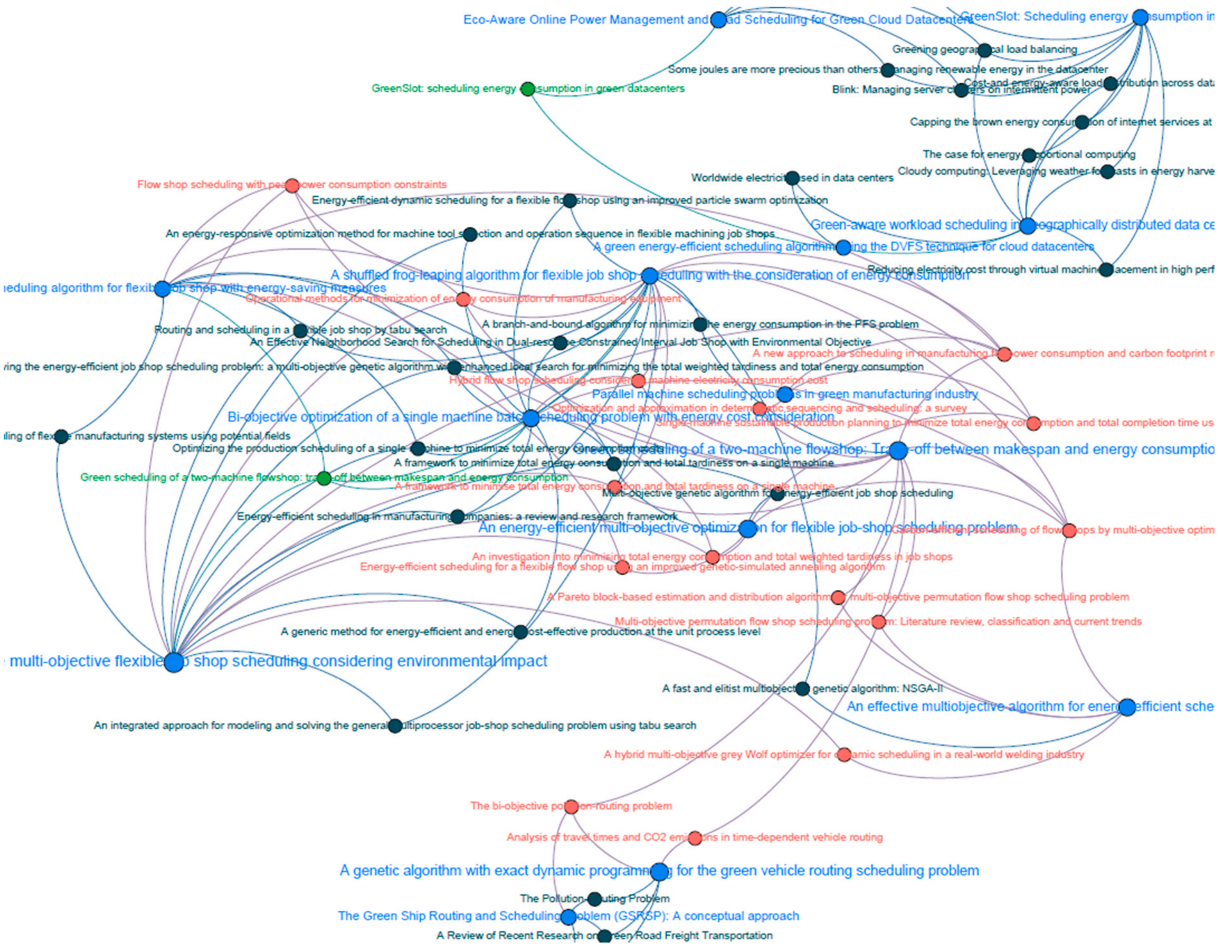

Fig. 10. Most cited publication and bibliographic reference network.

Table 8
Main relationships between most cited publications and references [70-91].

	MOST CITED PUBLICATIONS											
	[70]	[71]	[72]	[73]	[74]	[75]	[76]	[77]	[20]	[60]	[59]	[64]
Times cited	48	48	49	51	51	55	62	69	70	87	91	148
REFERENCES [78]			x	x						x	x	x
[79]		x						x				x
[13]	x				x				x	x		x
[80]								x				x
[81]					x				x	x		x
[82]					x				x	x		x
[83]			x		x							
[84]										x	x	x
[85]					x					x		x
[86]	x									x	x	
[87]				x							x	
[88]			x									x
[89]			x									x
[90]					x				x		x	
[91]	x											x
[64]				x	x				x	x		
[65]						x	x					

method and objective (economic-oriented (makespan, energy cost, …) or environmental-oriented (energy consumption, peak power consumption, carbon emissions,..)). Therefore, the main mission of the most cited references among the most cited articles is to establish the research framework related to scheduling, which is the basis on which new research related to green scheduling is based. In terms of organizations, as shown in Fig. 11, the groups formed in the network indicate that the references are the result of collaborative work between different organizations, including, as a main group, the research obtained after the collaboration between HEC de Montréal (Canada), Eindhoven University of Technology (Netherlands), University of Southampton (UK); and other collaborations groups, such as, Nanjing University of Aeronautics

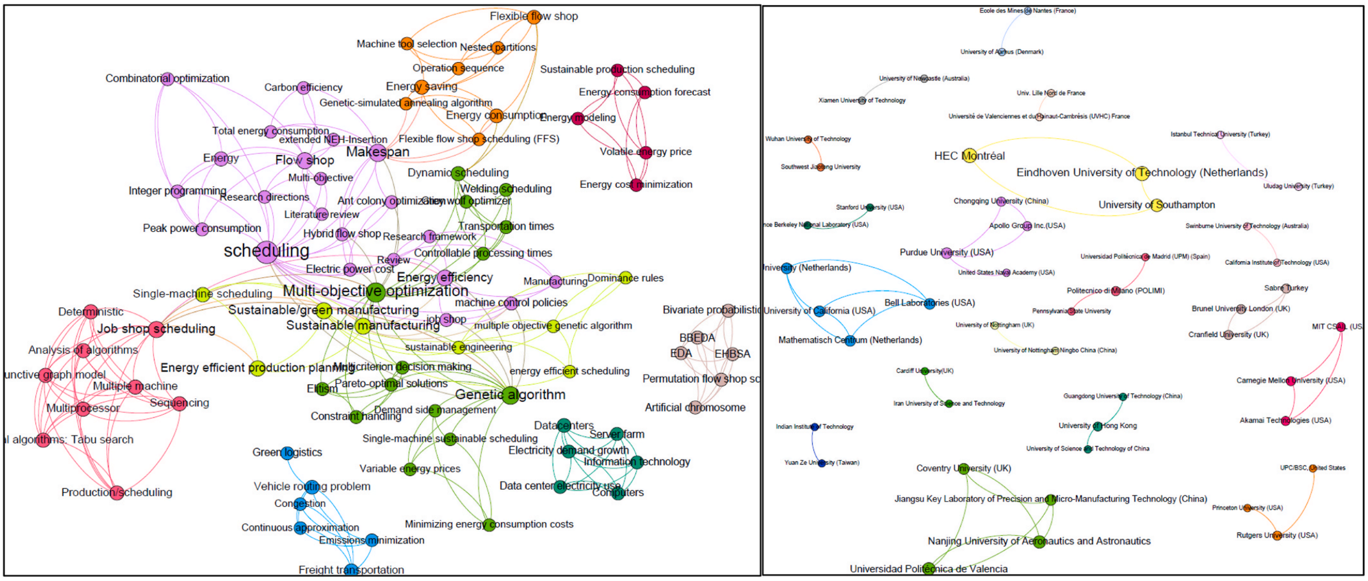

Fig. 11. Reference keywords and affiliation network.

and Astronautics (China), Polytechnic university of Valencia (Spain) and Coventry University (UK), among others.

5. Discussion and conclusions

The successfully applied methodology generated information that showed the evolution of the green scheduling research field, identifying when, where, who and about what the academic community is researching. The field of green scheduling research recently began to gain strength among the scientific community in 2006. The number of articles grows moderately, however, the number of times these articles have been cited has increased markedly in the last four years, which allows us to conclude that green scheduling research is becoming an important source of knowledge for the research community, both in research areas related to Computer Science as well as Engineering. The sources of diffusion of research related to green scheduling is quite broad, i.e. it is widely distributed, with the main scientific journal being the Journal of Cleaner Production, whose research has a very high impact factor.

As for the geographical location of the scientific production, it is widely spread over the three continents, with China standing out as the most productive, intermediary and influential on others, and also currently very active. Chinese organizations, mainly universities, have a high degree of national and international collaboration, most notably Tongji University for its intermediary work. The USA is the second most productive country, but with the exception of the University of Pennsylvania, which had a period of intense research in 2011–2013, research is widely distributed among different university organizations. As for Europe, countries such as France and the UK are prominent, both in terms of production, collaboration and influence. The University of Évry plays an important role in terms of intermediation and influence in collaborative scientific development, both nationally and internationally. In addition, the results obtained allow us to conclude that countries with less scientific projection (such as Spain or Pakistan, among others) present a high degree of international collaboration in order to develop their research.

The number of new research topics generated in recent years defines a stage of scientific growth in this area of knowledge. Research topics are grouped into different clusters that synthesize different approaches to the application of green scheduling, underscoring that all clusters feature energy saving as a key element. There are three main application groups: green scheduling in production, green scheduling in computation areas and green scheduling in transportation (see Table 5). The main research topics are based on the development of new methods to improve manufacturing models on production, with the main objective of minimizing the impact on both the economic and environmental dimensions, which is supported by the research scheme followed by the most productive organizations (see Fig. 9). Its main fields of application are flow-shop, job-shop, and parallel machine models in multi-objective or bi-objective systems. In addition, the study has allowed us to identify other applications and models that, despite not being directly related to productive systems, are of great importance in the application and research environment of green scheduling, such as cloud computing (data center) and green communications, that integrate the green scheduling group in computation areas. The data center industry, in particular, is considered the fifth most energy-intensive industry in the world [17], which is why minimizing carbon emissions becomes one of its target functions to be achieved through task scheduling. To a lesser extent but generating a field of application, the application of green scheduling in transportation is identified, mainly focused on maritime transportation. The results of the research allow us to describe a research framework that will be useful to conceptualize future research that develops new methods, or looks for new areas of application or purposes. In addition, the obtained main fields of research, such as the production chain and computer systems, verifies that the main sources of dissemination are the Journal of Cleaner Production and IEEE Access, categorized in the areas of Engineering, Environmental and Computer Science, and positioned in the first quartile, which confirms the high quality of the research carried out.

The most cited publications make it clear that the different algorithms created for energy optimization in scheduling are the key nodes for its dissemination. Those publications have a common purpose, namely to work on the development of new or improved algorithms for green scheduling. In addition, these articles become a reference for future research, since citation calls for citation, as Shibata, Kajikawa and Matsushima [54] study in their research. In addition, the analysis of their references through techniques such as co-citation, establishes that the most cited references support the research framework related to scheduling that serve as a conceptual framework for the publications in the dataset studied.

Future research may be focused on investigating those patents whose purpose is the commercial development of green scheduling oriented technology applications, which would add an application level to this research focused on the identification of research fields related to green scheduling oriented technologies, and their scientific development environment.

Author statement

Izaskun Alvarez-Meaza and Enara Zarrabeitia-Bilbao: Conceptualization, Methodology, Data curation, Investigation, Software and Writing- Original draft preparation. Gaizka Garechana-Anacabe: Visualization, Software. Rosa Maria Rio-Belver: Investigation, Supervision and Validation. Izaskun Alvarez-Meaza and Rosa Maria Rio-Belver: Writing- Reviewing and Editing.

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