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Thirty Years of Flexible Job-Shop Scheduling: A Bibliometric Study

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Abstract

Industry 4.0 introduced a new change in paradigms and technologies in the industry. In the shop schedule, it gains a holistic viewpoint and online demands, real-time and reactive methodologies. Developments in the scheduling area are critical to success. First addressed by Brucker and Schlie in 1990, the Flexible Job-Shop Scheduling Problem has been attracting researchers and practitioners over the last decades. This body of research may be helpful to address the industry high flexibility scheduling problems. This article uses a bibliometric approach to study three decades of research on this problem. The main results identify the most prolific research areas, journals, institutions, countries, and authors, and co-citation networks that revealed the most influential authors, as well as their most relevant works. A conceptual analysis based on keywords burst and occurrences helped to identify the latest research evolution and trends; allowing to recognize alignments and gaps within Industry 4.0.

Keywords: Flexible Job-Shop Scheduling; Production Scheduling; Operations Research; Bibliometrics.

1. Introduction

In the last few years, we have witnessed a notable change in paradigms and technologies in the industry that justifies the introduction of a new evolutionary stage. We are at the beginning of the so-called fourth industrial revolution, also known as Industry 4.0 (I4.0) [1, 2]. Fundamental concepts of this new paradigm are smart factory, cyber-physical systems, self-organization, new systems in distribution and procurement, new systems in distribution of products and systems, adaptation to human needs, and corporate social responsibility [3]. Those concepts tend to promote the

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increasing of flexibility, productivity, efficiency, and sustainability, ultimately ensuring competitiveness in the global market. I4.0 is promoting the emergence of a smart manufacturing environment system supported by novel and emerging technologies. These technologies include cloud computing, Mobile devices, IoT platforms, Fog/Edge computing, location detection technologies, advanced human-machine interfaces, Authentication & fraud detection, 3D printing, smart sensors, big data analytics and advanced artificial intelligence (AI) algorithms, Digital Twin, multilevel customer interaction and customer profiling and augmented reality/wearables [4].

This new production paradigm introduces new perspectives to schedule; it gains a holistic viewpoint and demand online, real-time and reactive methodologies [5]. In shop scheduling, due to it flexibilities requests, Flexible Job-Shop Scheduling Problem (FJSP) and Flexible Flow-Shop Scheduling Problem (FFSP) research is the base to tackle these emerging scheduling problems [5, 6].

The FJSP is considered as a generalization of the traditional Job-Shop Scheduling Problem (JSP) and the parallel machine environments. There is a set of work centers with at each several identical machines in parallel. Each job requires processing at each work center in one of the machines and has its own route through the work centers shop. In the case of all the jobs having the same route it is classified as flexible flow shop problem (FFSP) [7]. FJSP becomes more complicated than the classical JSP since it adds another decision level to the sequencing problem, i.e., selecting the job routes [8]. Brucker and Schlie initially introduced this problem in 1990 [9], and since then, it has been attracting researchers and practitioners. FJSP is the base for reconfigurable machine tools (RMTs) scheduling [10], that according to Qin et al. [11] are the production systems with most potential to achieve I4.0 objectives such as the ability of self-optimization and self-configuration. The problem is also used to address real-time scheduling [12], and some approaches are making use of AI algorithms, like Machine Learning, to solve it [13]. These examples show how the problem strong relates to I4.0 concepts. The developments in the area are critical to manufacturing systems success. It is crucial to understand how this research has been conducted and reveal the relations with the newest production paradigms. Motivated by the 30th anniversary of the publication of the seminal work of Brucker and Schlie [9], this paper develops a study to understand how the research of FJSP has been evolved over recent years and establish future directions. Has the research kept up with challenges and technologies associated with these new paradigms related to I4.0? To address this question, we have applied scientometric and bibliometric methods.

Bibliometrics refers to the use of quantitative statistical techniques to analyze bibliographic data from published literature, such as year of publication, authors, country of origin, among others [14]. The scientometric is a sub-field of bibliometrics focused on scientific literature. Its research methods enable visualization and mapping of a knowledge domain. The development of scientometric studies provides a general outline and an overall structure of the field that is analyzed. The underlined methods are useful to identify the most relevant woks and authors, current trends and directions for future research work.

In this paper, we make a descriptive analysis of the most prolific research areas, journals, institutions, countries, and authors addressing the FJSP. To unveil the intellectual structure, we use co-citation networks, and to identify the most influential authors as their most relevant works, we have used a data visualization software to map graphically existing relations. A body of research is thus established, which is a beginner's basis for studying this problem. A precise analysis of the keywords and their evolution in the last years is performed, seeking to identify changes, alignments with I4.0, trends, and directions for prospective studies.

The rest of the paper is structured as follows. Section 2 describes the data collection methodology and the scientometric technique used. Section 3 presents the bibliometric analysis results in two steps. Firstly, a global descriptive analysis of the last 30 years is presented, and secondly, the conceptual structure of evolution and trends in this research field is discussed. In the last section, we present the concluding remarks.

2. Methodology

Our study follows the bibliometric methodology proposed by Zupic and Carter [15], which can be summarized in five-steps: i) study design, ii) data collection, iii) data analysis, iv) data visualization, and v) interpretation.

The bibliometric data was gathered from the Web of Science (WoS) [16]. Being one of the primary bibliographic sources of information, WoS uses the Web of Science Core Collection database. The database has more than 21.100 peer-reviewed high-quality scholarly journals published worldwide in over 250 disciplines. The access to the database took place on January 2 of 2020, and a general search by topic was performed using the keywords: "flexible" AND

"job" AND "shop" AND "scheduling". The general search by topic retrieved all the published documents with the keywords on the title, abstract, author keywords, or Keywords Plus. The analysis considered all documents published between 1990 and 2019, being the work of Brucker and Schlie [9] the earliest dated document.

The WoS search resulted in 1476 documents classified as follows: 65% (961) of the documents were classified as articles, and 37% (544) as proceedings papers. Some of the documents have more than one classification. The remaining minor categories were review (16), book chapter (12), early access (11), editorial material (4), meeting abstracts (4), correction (2), book (1) and note (1). Journals and books covered by WoS Core Collection were assigned to at least one WoS category in its indexing lists. And each Web of Science category was mapped to one research area.

For this study, we considered only the articles written in the English language. Thus, of the 961 documents retrieved, only 952 have been included in the analysis. For this collection of articles, tags such as author, title, abstract, country, citation record, author affiliation, author keywords have been saved. In addition to that, data provided by the Keywords Plus (WoS extra keywords tags) was also collected.

The keywords were pre-processed, and those with plurals or similar meanings were aggregated into a single primary term (e.g., "energy efficiency" and "energy-saving" were merged into "energy consumption"). Early Access Articles awaiting for year assignment were kept in the collection and considered as 2019, since these works may unveil trends.

The primary software resource for the bibliographic study was *bibliometrix* [17]. This tool is open-source software, programmed in R, that provides powerful functionalities for data analysis and visualization. Besides, we used CiteSpace [14] to identify the author's keywords and the Keywords Plus with the strongest citation bursts.

3. Bibliometric Study

The results of the bibliometric study are presented in two steps. The first step presents a descriptive analysis of three decades of research contributions for the FJSP. The most influential authors and the structure of the research work are carefully analyzed. It is established a set of works which is a beginner's basis for studying this problem. The second step is mainly focused on conceptual structures and trends. It shows the evolution of the keywords in the last years, seeks to detect trends and identify emerging concepts within the context of I4.0.

3.1. A Three Decades Global Analysis

The FJSP area has grown significantly over time. Figure 1 presents the annual number of articles published between 1990 and 2019 and the citation number trend line.
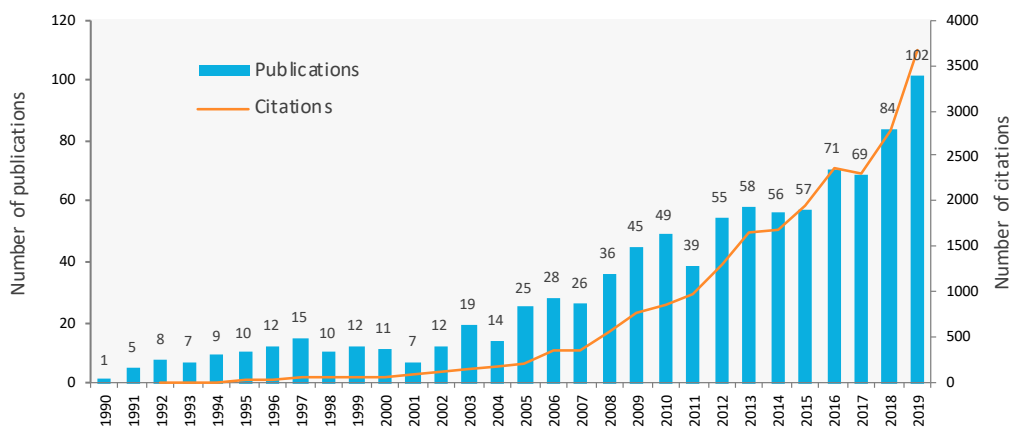

Fig. 1. The total number of publications and the total number of citations in WoS, 1990 – 2019.

The results underline a significant growth of 17% annual average rate. Globally, Science and Engineering publications output grew at an average annual rate of 6% between 2004 and 2014. The annual number of citations shows exponential growth, as follows the number of publications. The paradigm change in production to Flexible Production Systems can explain this growth of research interest. Despite the 30 years of research, the field of FJSP shows no signs of stagnation or decline.

The top 3 WoS categories are Operations Research Management Science, Engineering Manufacturing, and Engineering Industrial, which are followed by Computer Science Interdisciplinary Applications and Computer Science Artificial Intelligence. As in many other research areas, artificial intelligence seems to be gaining prominence in addressing the FJSP.

Regarding the publication research areas, the ten most productive classes are presented in Figure 2. Engineering has been ranked first, with 66% of the articles. Second, Operations Research Management Science is *Ex eaquo* with Computer Science, both with 39%. Apart from the publications in the obvious areas, publications in the field of Environmental Sciences Ecology also stand out with 1% (14 articles), all published in the last five years. This situation may reflect the fact that environmental and energy-saving concerns are gaining importance in this field.
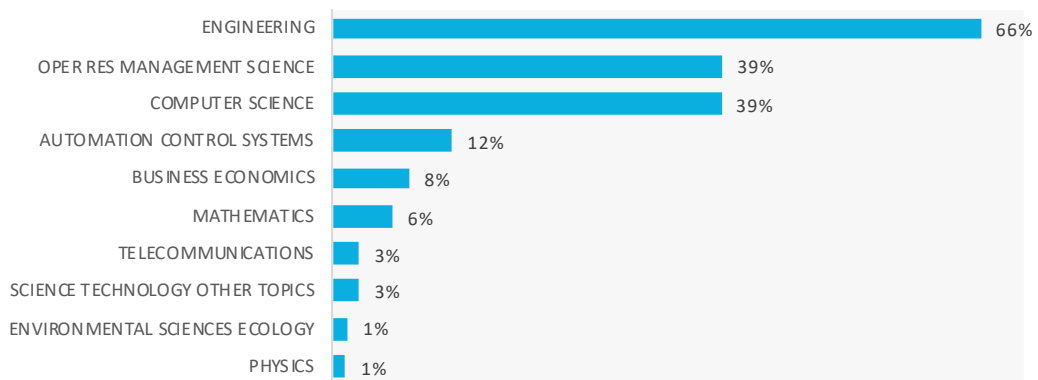

Fig. 2. The 10 Research Areas with most publications, 1990 – 2019.

Table 1, lists the ten most productive sources, institutions, and countries represented in the collection. From this table, it can be seen that the International Journal of Production Research is on the top of the source list with 123 publications. The following are the International Journal of Advanced Manufacturing Technology, Computers & Industrial Engineering, European Journal of Operational Research, Journal of Intelligent Manufacturing, with 81, 59, 39, and 34 publications, respectively. Those are the core sources applying Bradford's Law classification. Out of the core, we find Computers & Operations Research, International Journal of Production Economics, Expert Systems with Applications, IEEE Access, and Applied Soft Computing. Except for IEEE Access, all the other top publications are also the ones with more citations and higher H-index. IEEE Access and Applied Soft Computing, started their publications in this millennium, 2014 and 2004 respectively (contrarily to the others that started in the '90s), and that may be the reason why IEEE Access is not on the top 10 of the most cited sources.

Among the institutions, the Islamic Azad University at Tehran, in Iran, is the leading institute in terms of the number of documents published with 38 articles. Huazhong University of Science and Technology from China with 36 papers and the University of Tehran from Iran with 33 papers are in the second and third spots, respectively. Considering the list of the top 10 institutions, 6 institutions are from China, 3 from Iran, and 1 from Singapore. It can be seen that China and Iran dominate the other countries in terms of institutions publishing FSJP research papers. China published more than 50% of the collected articles, with a total of 488 articles, followed by Iran with 237 papers and the USA with 135 papers. After these, Taiwan (92), France (72), India (72), Turkey (64), South Korea (55), Japan (44), and Germany (41) stand out.

Table 1. The rank of the 10 most relevant sources, institutions, and countries, 1990 – 2019.

R*	Sources	TP*	Institutions	TP*	Country	TP*
1	INTERNATIONAL JOURNAL OF PRODUCTION RESEARCH	123	ISLAMIC AZAD UNIV	38	CHINA	488
2	INTERNATIONAL JOURNAL OF ADVANCED MANUFACTURING TECHNOLOGY	81	HUAZHONG UNIV SCI AND TECHNOL	36	IRAN	237
3	COMPUTERS & INDUSTRIAL ENGINEERING	59	UNIV TEHRAN	33	USA	135
4	EUROPEAN JOURNAL OF OPERATIONAL RESEARCH	39	TSINGHUA UNIV	24	TAIWAN	92
5	JOURNAL OF INTELLIGENT MANUFACTURING	34	LIAOCHENG UNIV	21	FRANCE	72
6	COMPUTERS & OPERATIONS RESEARCH	30	WUHAN UNIV TECHNOL	19	INDIA	72
7	INTERNATIONAL JOURNAL OF PRODUCTION ECONOMICS	22	DALIAN UNIV TECHNOL	17	TURKEY	64
8	EXPERT SYSTEMS WITH APPLICATIONS	21	SHAHID BEHESHTI UNIV	17	SOUTH KOREA	55
9	IEEE ACCESS	17	JIANGNAN UNIV	16	JAPAN	44
10	APPLIED SOFT COMPUTING	15	NANYANG TECHNOL UNIV	16	GERMANY	41

* R = rank; TP = total production

Based on the number of publications and their annual citations, data of the most productive authors were sorted and compiled. The results are shown in Figure 3, with the representation of their production timeline, the relative annual production (represented by the bubble size), and the relative annual citations (represented by the color intensity of the bubble). The five most productive authors are Zandieh M, Pan QK, Wang L, Gen M, and Wang Y. Except for Wang Y and Ji ZC, all the other authors shown in Figure 3 are also the top 15 most cited and have the highest H-index. Analyzing the figure, it is noticeable that most of those authors' activity begins after 2005. According to Figure 1, that was the period when the research of FJSP has a noticeable growth.
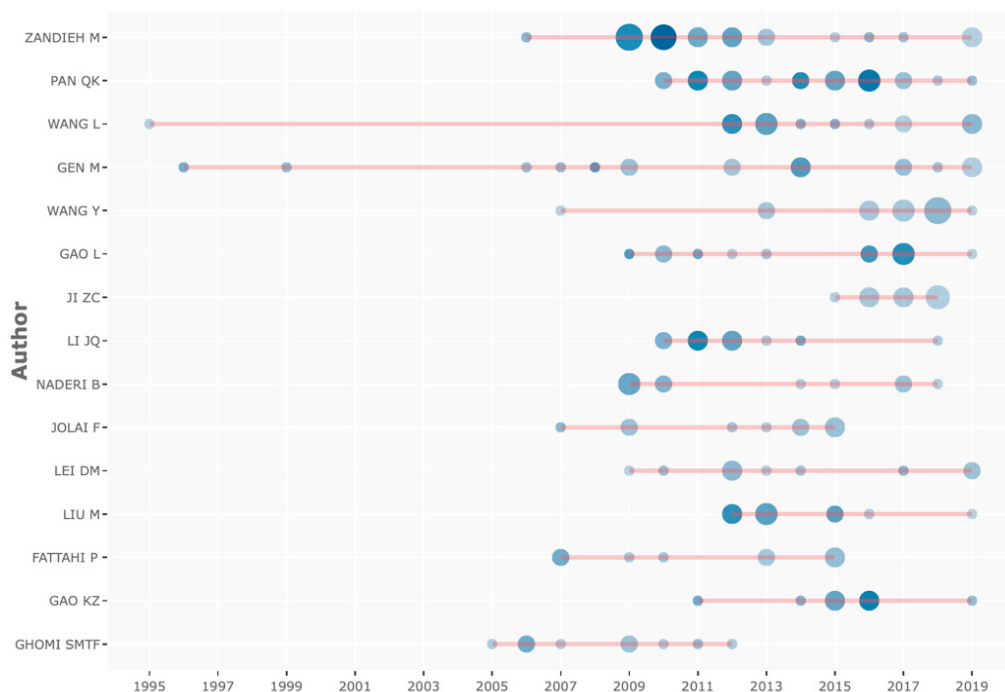

Fig. 3. Production overtime of the 15 most productive authors (bubble size is proportional to the n. of documents, and the color intensity is proportional to the total citations per year).

An author co-citation network was used to map the author's citation context [15] and identify the most relevant authors [18]. To quantify the importance of the nodes in the co-citation network, it was used the betweenness centrality metric. The nodes with higher betweenness centrality are seen as pivotal because they can represent paradigm shifts [14].

The authors with the highest betweenness centrality on the co-citation network are Brandimarte P., Garey MR, Kacem I, Gao J, Pezzella F. In sixth, Brucker P, who have the work we considered as seminal, followed by Wang L, Xia WJ, Zhang GH, and Li JQ. From this rank, the most influential authors that are cited but do not have any document in the collection are Garey MR and Dauzère-Pérès S. Besides their high betweenness centrality index, these authors have articles in the list of the most referenced documents in the collection; this confirms their influence. It may be assumed that these authors produced work that contributes with a solid ground to the development of the area but does not deal directly with FJSP.

To better understand which publications these authors owe their position to, a co-citation network of papers is used to rank the most important documents they have published. Table 2 shows the rank of the 10 articles with the highest betweenness centrality index in the network. The cited references column denotes the number of times these articles have been cited within the collection. As seen in Table 2, there is a close match between the ranking of the local documents with a higher betweenness centrality index and the cited references ranking. Those articles are not only co-cited with a large set of papers (some of them unrelated between themselves) as they are the most used references for the collection articles. These two relations confirm their influence in the area of FJSP, and as relevant publications in the collection are a good start point for researchers debuting.

Crossing Table 2 articles with the author's co-citation network, it becomes evident that Garey MR's importance is due to a 1976 work on the complexity of flow shop and job shop scheduling [19]. Brandimarte P is the author of one of the articles in our collection, but his top position as a relevant author is due to another work titled "Routing and scheduling in a flexible job shop by tabu search" [20]. This article is not part of the analyzed collection because it is not indexed in the WoS. Another example of a non-indexed relevant work present in Table 2 is Mastrolilli's paper, "Effective neighbourhood functions for the flexible job shop problem".

Table 2. The 10 articles with the highest betweenness centrality in the co-citation network.

R*	Cited Article Title	Authors (year)	CR*
1	The complexity of flowshop and jobshop scheduling	Garey et al. (1976)	182
2	Routing and scheduling in a flexible job shop by tabu search	Brandimarte (1993)	219
3	A genetic algorithm for the Flexible Job-shop Scheduling Problem	Pezzella et al. (2008)	175
4	Job-shop scheduling with Multi-purpose machines	Brucker and Schlie (1990)	140
5	An effective hybrid optimization approach for multi-objective flexible job-shop scheduling problems	Xia and Wu (2005)	160
6	Approach by localization and multiobjective evolutionary optimization for flexible job-shop scheduling problems	Kacem et al. (2002)	175
7	An integrated approach for modeling and solving the general multiprocessor job-shop scheduling problem using tabu search	Dauzère-pérès S (1997)	130
8	A hybrid genetic and variable neighborhood descent algorithm for flexible job shop scheduling problems	Gao J (2008)	131
9	Effective neighbourhood functions for the flexible job shop problem	Mastrolilli and Gambardella (2000)	134
10	An effective hybrid particle swarm optimization algorithm for multi-objective flexible job-shop scheduling problem	Zhang et al. (2009)	112

* R = rank; CR = cited references

Dauzère-Pérès S is represented in Table 2 due to a 1997 work [21]. This article is an FJSP work, but "flexible" is not found in any of their tags; for that reason, it was not recognized as FJSP work during the WoS search. Due to this analysis, previous assumptions about the work produced by this author may now be clarified. In this work, the author introduced an extended version of the disjunctive graph model that takes into account the difference between JSP and FJSP: operations have to be assigned to machines. This model becomes one of the most used in the literature.

These results show the power of these co-citations analysis to overcome some methodology limits (works non-indexed or not retrieved during the search) and find the relevant articles not found with a global or local citation score analysis. Some of the publications shown in Table 2 are seminal works in the evolution of the FSJP field.

Once the most influential articles had been identified, it is crucial to map their evolutive relation to understand the state of the art better and discover the linkages among authors. To accomplish that, an historiographic map [16] of the top 15 most local cited articles has been generated, see Figure 4.

In the historiography, the story begins with the seminal paper of Brucker and Schlie in 1990 [9], and this is the first document associated with the FJSP. However, in this work, the authors mentioned the FJSP as a JSP with multi-purpose machines. In 1994, Hurink et al [22] pursued that work and proposed a Tabu search heuristic to solve it. These articles give rise to a dominant line of research only compared with the one Kacem et al [23, 24] in 2002. From our collection, these are the first authors that referred to the FJSP concept and proposed several metaheuristics to solve it. In general, the other papers sustain their relevance to their solution approach.
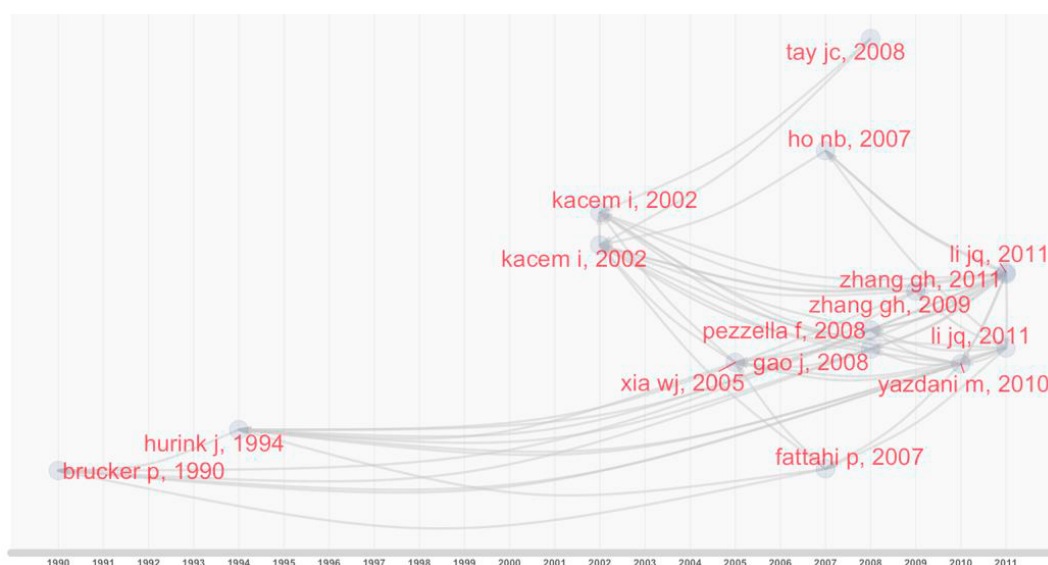

Fig. 4. Historiograph of the 15 most locally cited articles in the collection.

3.2. Conceptual Structure Evolution and Trends

To reveal the conceptual structure of the FJSP, the occurrence of author keywords and Keywords Plus is analyzed. A global temporal analysis is performed to show the common concepts associated with the research area and to uncover evolutions and trends.

Burst detection is a kind of temporal analysis used to find features that have a high intensity over a finite duration of periods. CiteSpace burst analysis detected 21 Key-words Plus, and 13 author keywords with the strongest citations bursts. The longest detected bursts reflect the use of words such as scheduling and flexible job-shop scheduling problem. Those were expected words because they describe the problem and are commonly used. In the author's keywords were identified bursts of words connected with solution approaches: simulation in 1993-2003, heuristics in 1997-2006, simulated annealing (SA) in 2006-2009, local search (LS) 2013-2017, particle swarm optimization (PSO) in 2015-2019. Simulation in 2002-2011 was also detected as a burst in Keywords Plus. Besides simulation, in the Keywords Plus stand out words like dependent setup times in 2012-2015 and power consumption in 2017-2019. The latest bursts indicate that, at the moment of this study, PSO is a popular solution approach, and energy consumption is becoming a relevant application area.

Even without any burst in the last 30 years, some keywords play a fundamental role in the FJSP conceptual structure. An overview of the keyword occurrence is presented to identify the concepts associated with those words.

A co-occurrence of analysis confirmed that the most common keywords are the ones with the higher betweenness centrality value – the most relevant. Table 3a presents the most common author keywords occurring in the last 30 years, for the global view, and in two different time slices: 1990-2014 and 2015-2019. The fundamentals of I4.0 arise earlier, but it term came in 2011 from an innovation project of the German government. The period of the last five years seems reasonable to detect the influence of these new paradigms. This division is asymmetric in time but more balanced concerning academic production. Globally, 40% of the papers have been published in the last 5 years.

The authors' keywords were preferred over Keywords Plus because the main goal of the analysis is to reveal recent trends. Keywords Plus is based on article references, and if that article introduces new trends, those may not be captured. It should be noted that even the keywords chosen by the authors are a little biased concerning the year because, in many articles, the year of publication is later than the year of acceptance and public availability. However, both keyword types underwent a detailed analysis.

In line with the burst analysis, the global ranking presented in Table 3 reveals that flexible job-shop scheduling and scheduling are the keywords with the highest relevance. Genetic Algorithm (GA) is the most common method keyword. This is easily understood once it is one of the most versatile metaheuristics. Over the last 30 years, in addition to the resolution methods, stand out words that related to the problem characteristics, such as sequence-dependent setup times or dynamic scheduling and solutions objectives like multi-objective or makespan.

Comparing the two-time slices of Table 3 allows identifying the evolution of concepts in recent years. The presence of energy consumption confirms the trend that research is becoming focused on energy-saving issues. The previously keyword burst identified on "energy consumption" and the presence of the Environmental Sciences Ecology area in the main research areas are consistent with that finding.

The emphasis in "dynamic scheduling" and "fuzzy processing time" indicates that the problems addressed are introducing more sophisticated features of the real-world systems. Off the rank goes sequence-dependent setup times, where is also dual resource-constrained. No other keywords related to FJSP extensions are in the top 10 list. However, transportation time was one of the most frequent author's keywords in 2019.

Table 3. The rank of the most common author keywords occurrence

R	Global	1990-2014	2015-2019
1	flexible job shop scheduling	scheduling	flexible job shop scheduling
2	scheduling	flexible job shop scheduling	scheduling
3	genetic algorithm	genetic algorithm	genetic algorithm
4	job shop scheduling	flexible manufacturing systems	multi-objective optimization ⇧
5	flexible manufacturing systems	job shop scheduling	job shop scheduling
6	makespan	makespan	⇨ energy consumption
7	multi-objective optimization	heuristics	makespan
8	heuristics	simulation	local search ⇧
9	simulation	tabu search	dynamic scheduling ⇧
10	tabu search	multi-objective optimization	tabu search
11	local search	simulated annealing	particle swarm optimization ⇧
12	simulated annealing	flexible flow shop	heuristics ⇩
13	dynamic scheduling	local search	optimization ⇧
14	flexible flow shop	dynamic scheduling	flexible flow shop
15	particle swarm optimization	dispatching rules	simulation ⇩
16	sequence-dependent setup times	flexible flow line	variable neighborhood search ⇧
17	dispatching rules	sequence-dependent setup times	⇨mixed-integer linear programming
18	optimization	production scheduling	flexible manufacturing systems ⇩
19	production scheduling	flow shop	fuzzy processing time ⇧
20	ant colony optimization	particle swarm optimization	simulated annealing ⇩

Regarding general solutions methodology approaches, optimization stands out as the simulation goes down with dispatching rules, the latest leaves the list. Exact methods and metaheuristics overcome heuristics. Finding the best possible solutions is indeed the trend confirmed by the emergence of mixed-integer linear programming (MILP). Advances in computing, powerful hardware, faster solvers with effectiveness algorithms make those methods more promising. In the metaheuristic domains, besides GA, LS, PSO, and variable neighborhood search stand out. Still absent from this list, but a relevant mention, bee colony algorithm highlights as the most referred author keyword in 2019. SA loses relevance in this ranking. The rise in the occurrence of multi-objective optimization discloses trends in modeling decisions trade-offs.

The last year's evolution of keywords suggests that the tendency is to focus on more realistic problems, solving them for near-optimal multi-objective solutions, using mathematical programming and efficient metaheuristics. These developments are essential to deal with manufacturing systems characterized by increased flexibility, productivity, efficiency, and sustainability, like I4.0.

The term "Industry 4.0" is firstly reported linked to a German strategic plan and is later disseminated by other countries, mainly in Europe. There are similar strategic plans, such as "Industrial Internet" or "Made in China 2025" that are associated with the same production paradigms. This lack of globality can justify its absence from table 3. However, their related concepts are transversal and should emerge once in use. Table 3 does not expose words closely related to I4.0, like decentralized and data-driven scheduling, big data, Cyber-physical, digital twin or smart factories. Some works already couple these concepts with the FSJP but scheduling is referred to as a general allocation and sequencing problem or the problem is clearly described but not FJSP classified, as in Mourtzis work [25].

Meanwhile, simulation is present in table 3, and it may be a bridge to the digital twin concept. Simulation works may promote the development of complex virtual models, integrated with optimization algorithms; generating a digital twin of the physical system. Nevertheless, to get it close to the physical system data need to flow. The exploration of data-driven approaches is essential to improve those developments. The increase in the amount of data, and its availability in real-time, may change the global outlook of the problem, introducing new solution approaches or even reshaping it. The scheduling will become more holistic, potentially increasing efficiency. Also, the exploitation of decentralized scheduling may lead to the development of faster algorithms, as they optimize only part of the system, allowing more reactive systems. I4.0 related artificial intelligence techniques as machine learning or reinforcement learning showed high potential in operational research in recent years [2]; could be expected that they stand out as a trend. Cloud computing and parallel processing will provide computational support for the virtual system needs.

In general, the keywords indicate that FSJP research has focused more on mathematical models and approaches to its resolution. There is a development in the same direction as the I4.0 paradigms, however greater convergence is needed. A farther use of I4.0 concepts and technologies can profoundly change the way of modelling and solving the problem. More in-depth analysis of some topics can help clarify gaps and reveal promising directions to further research.

4. Concluding Remarks

This study addresses the evolution of FJSP research in the past 30 years, focusing on exposing its involvement with I4.0 in the last years. Based on bibliometric analysis, the most influential authors and the most relevant articles are presented, providing solid bases for future researchers. The conceptual evolution analysis shows that FJSP research connected with energy-saving issues is gaining relevance, keeping up the world's global concerns. The addressed problems are becoming more complex, reflecting real-world systems, but no particular extension of FJSP is spotlighted. Optimization stands out over simulations and dispatching rules. The exact methods and metaheuristics are taking advantage of technological progress into multi-objective decision-making solutions. Although the referred features are expected under the context of I4.0, there is still the need to improve this convergence. Relevant I4.0 words like digital twin, data-driven approaches, artificial intelligence or machine learning have not yet gained expression. Due to its applicability and potential, that can be a promising direction to further research.

The main limitations of this study are that only the WoS database and only articles were collected; however, it is expected that the main findings (the core relations and trends) would be similar to broader research. The analysis proved to be capable of revealing relevant authors and works out of the collection. This study does not provide an in-deep interpretation of the paper's content but points them as a start for further work.

Acknowledgements

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