Results in Control and Optimization 14 (2024) 100350

Contents lists available at ScienceDirect

Results in Control and Optimization

journal homepage: www.elsevier.com/locate/rico

Applications of constraint programming in production scheduling problems: A descriptive bibliometric analysis

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ARTICLE INFO

Keywords:
Production scheduling
Artificial intelligence
Constraint programming
Methodi ordinatio
Bibliometrix

ABSTRACT

Production scheduling is a class of widely studied combinatorial optimization problems. Given the complexity of the most addressed production environments several solution procedures have been proposed. In recent years, operational researcher practitioners have been paying attention to solving production scheduling problems using constraint programming, and growing interest in this research domain has been evidenced. The aim of this study is to report a descriptive bibliometric analysis of applications of constraint programming in production scheduling problems. The scope of the study is limited to reviewing 170 scientific papers published between 1992 and 2023 from the Scopus and Web of Science databases. In our proposed research questions, we could address the main topics studied, the most studied performance measures, and the profile of the analyzed documents. Furthermore, we could identify the main gaps and present suggestions for future research.

1. Introduction

1.1. Background

Nowadays, several real-world problems in production operation and management can be modeled as production scheduling problems. Traditionally, mixed-integer linear programming (MILP) models have been proposed to solve such problems, even though such models are not efficient solution procedures for large-sized test instances. Nevertheless, a mathematical formulation can be of great value for describing the characteristics of the problem under study.

In the last decades, with the development of computers and the conception of artificial intelligence techniques, new paradigms to model combinatorial optimization problems have been proposed. In this context, constraint programming (CP) has been evidenced as a competitive alternative to mathematical programming formulations. The use of logical constraints can represent a given combinatorial optimization problem more compactly, presenting gains in terms of the specification of problem characteristics and the reduction of the search space [1].

Production scheduling can be defined as determining where and when the necessary operations for a product will be allocated and carried out, defining dates to start and complete the necessary operations [2]. This area is dedicated to optimizing the allocation of tasks to available resources in a production system during a scheduling horizon. In this way, the study of production scheduling problems is important to make better decisions to improve classic problems in the industrial environment, whether large, medium, or small size, such as reduction of lead time, reduction of setup times, and better utilization of bottleneck resources [3]. For more

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https://doi.org/10.1016/j.rico.2023.100350
Received 28 September 2023; Received in revised form 5 November 2023; Accepted 21 November 2023
Available online 23 November 2023

complex production environments, there is the opportunity for improvement in several approaches in the face of the characteristics and needs present in the real world. Therefore, studying different production environments and their computational modeling with CP is necessary, aiming to consider constraints that model the real systems to develop efficient resolution strategies.

Publications reporting bibliometric analysis for production scheduling problems are still in the early stage. Recent contributions addressed the non-permutation flow shop [4], no-wait flow shop [5], flexible job shop [6], flow shop group scheduling [7], and energy-efficient hybrid flow shop [8]. Concerning solution methods to solve global optimization problems, a recent bibliometric analysis addressed metaheuristic-based solution approaches [9].

1.2. Research gaps and objective

Taking this into account, the researchers of the production scheduling domain have paid attention to CP techniques, leading to a growth in the number of contributions in the research line. From the nineties until the present, several documents have been published using CP in production scheduling problems. To the best of our knowledge, there have been no studies surveying these previous publications.

This paper aims at presenting a bibliometric analysis of applications of constraint programming in production scheduling problems. We selected 170 documents published in Scopus and Web of Science databases. Using the Bibliometrix package [10] from R software (https://www.r-project.org/), we analyzed such references. We determined the main topics addressed, the most relevant objective functions, the main characteristics of gathered documents, and the future research trends.

1.3. Outline

The rest of this paper is organized as follows. Section 2 presents the literature overview. Section 3 describes the research methodology. Section 4 illustrates the main findings. Section 5 addresses the proposed research questions. Finally, Section 6 presents the main conclusions.

2. Literature overview

CP is a modeling paradigm for solving combinatorial optimization problems, such as routing and scheduling problems [11]. It combines logic programming and constraint-solving techniques to solve optimization problems. It is a recent technique when compared to linear programming, that has shown promising results in solving several problems, mainly in production scheduling problems, as in [12–14].

A constraint programming model has the same linear mathematical programming model characteristics: parameters, objective function, decision variables, and constraints. However, it is solved by exploring the problem domain, analyzing the constraints, and defining and setting values for the variables with a tree search process [15].

Constraint programming in production scheduling problems has several advantages. Due to the use of logic programming in modeling, it is possible to represent scheduling problems with less constraints, using logical arguments, linear and non-linear operators and cumulative constraint (using to model additional resources or limited workers). Therefore, it is possible to solve the models with reduced computational times.

The main differences with linear programming are that constraint programming uses logical constraints for the problem and applies heuristic techniques to reduce the problem's search space. Moreover, constraint programming finds feasible solutions quickly due to the problem domain's exploration.

Another difference is that linear programming can represent problems with both continuous and discrete variables, making it easier to model mixed problems. On the other hand, constraint programming is capable of representing problems with only discrete variables, and it is difficult to model problems of a continuous nature [15].

Constraint programming was not applied to solve production scheduling problems until the beginning of the 1990s, after further development in hardware, software, and algorithms. Paredis and van Rij [16] presented an integrated framework based on discrete event simulation and constraint programming to solve the job shop scheduling problem. Several performance measures can be evaluated in this tool, such as the makespan minimization. In the 1990s, two other contributions of constraint programming were presented to solve production scheduling problems: Zhou [17] addressed the job shop scheduling problem, and Pape and Baptiste [18] studied the open shop environment.

In the first decade of the 21th century, a slight increase in the scientific publications addressing the application of constraint programming to model production scheduling problems can be observed. The production environments studied in such studies are the open shop [19], job shop [20–27], single-machine [28,29], parallel machines [30–33], multipurpose batch plants [34], hybrid flow shop [35], and other production environments [36].

In the next decade, a significant increase in the number of documents can be observed, and dozens of contributions were published. Several contributions to distinct production scheduling problems can be observed, such as job shop [37–47], flexible job shop [48–52], parallel machines [53–61], single-machine [62–67], flow shop [68–73], open shop [74], and customer order scheduling [75].

During the current decade, the number of contributions addressing constraint programming and production scheduling has increased significantly. Operational research practitioners have paid attention to the following production environments: job shop [76–82], multiprocessor job shop [83], flexible job shop [84–91], hybrid job shop [92], distributed flexible job shop [93],

parallel machines [94–100], single machine [101,102], permutation flow shop [103–105], hybrid flow shop [106,107], distributed flow shop [108], distributed hybrid flow shop [109], open shop [110–113], customer order scheduling [114], scheduling with additional resources using cumulative constraints [97,115] and other environments [14,116–125].

Some real-world applications of constraint programming models are illustrated as follows: Lunardi et al. [14] presented a CP model for the online printing shop scheduling problem that is a challenging real problem that appears in the modern printing industry. Beauchemin et al. [126] proposed a case study in the metal 4.0 manufacturing industry about the dynamic allocation of human resources. The authors developed a CP model to assign tasks to the operators to minimize production delays dynamically. Bolsi et al. [127] presented a real-world application of integrated workforce allocation and scheduling of perishable products from a meat-producing company characterized by deterioration-prevention constraints. The authors implemented metaheuristics to solve the problem and a new CP model to estimate a lower bound. Finally, Jiang et al. [128] proposed an online dynamic scheduling model for smart manufacturing in a real-world steel plant. To solve the problem, the authors implemented a decomposition-based algorithm that combined MILP and CP models.

3. Research methodology

Given the large number of contributions published considering CP to solve production scheduling problems, we performed a descriptive bibliometric study [129]. In this context, we developed a research protocol that includes the research questions, keywords and search query string, inclusion and exclusion criteria, and search strategy. The proposition of research questions has an exploratory nature. Their purpose is to provide an overview of the current status of a given field. The development of the search query string plays a key role in the relation of the sampled documents with a particular area of study. Finally, our research protocol considers quantitative performance indicators to include the documents in our survey, seeking to collect the most relevant works.

3.1. Research questions

The choice of research questions (RQs) is of fundamental importance to the quantitative and qualitative analysis in a bibliometric survey. In our bibliometric study, we address the following RQs:

- RQ1: What are the main topics studied in research related to constraint programming and production scheduling problems?
- RQ2: What are the most studied objective functions?
- RQ3: When and where were the documents published?
- RQ4: What are the main gaps and research avenues on constraint programming in production scheduling problems?

3.2. Data source and software

Although several online databases allow keyword searches, we decided to restrict or survey only in Scopus and Web of Science databases. Such bases cover practically the totality of relevant journals, conferences, and books related to the production scheduling area.

We conducted the bibliometric review with the Bibliometrix package [10], using the R statistical tool. Since R is a recognized and open-source software widely used in scientific computing, we select this package in preference to other software. In addition, Bibliometrix has been used in several bibliometric studies [129,130].

3.3. Keywords and search query string

Aiming to define a strong search query string, we performed several simulations considering some terms related to the production environment and objective functions. Thereby, we built the following search string where no date range was specified: **((“constraint programming” AND “production scheduling”) OR (“constraint programming” AND “makespan”) OR (“constraint programming” AND “tardiness”) OR (“constraint programming” AND “flow time”) OR (“constraint programming” AND “completion time”) OR (“constraint programming” AND “lateness”) OR (“constraint programming” AND “flow shop”) OR (“constraint programming” AND “job shop”) OR (“constraint programming” AND “single machine”) OR (“constraint programming” AND “parallel machines”) OR (“constraint programming” AND “open shop”))**.

Table 1 illustrates the syntax conversion of the proposed query string in the formats of the Scopus and Web of Science databases. Recent studies have presented that these databases cover the most relevant documents published in the production scheduling domain [6,131]. Thereby, we used both bases to find research on constraint programming and production scheduling.

We performed the search in the above mentioned databases on October 31th, 2023. In this context, Table 2 shows the number of references found in each search source used and the total number of papers without duplicate references.

In resume, we obtained 276 documents. In our view, this number of documents is high for an adequate qualitative analysis. The procedure to select the documents for the bibliometric analysis is described below.

Table 1
Query strings in search sources used.

Search source	Query string	Applied filters
Scopus	(TITLE-ABS-KEY (“constraint programming” AND “production scheduling”) OR TITLE-ABS-KEY (“constraint programming” AND “makespan”) OR TITLE-ABS-KEY (“constraint programming” AND “tardiness”) OR TITLE-ABS-KEY (“constraint programming” AND “flow time”) OR TITLE-ABS-KEY (“constraint programming” AND “completion time”) OR TITLE-ABS-KEY (“constraint programming” AND “lateness”) OR TITLE-ABS-KEY (“constraint programming” AND “flow shop”) OR TITLE-ABS-KEY (“constraint programming” AND “job shop”) OR TITLE-ABS-KEY (“constraint programming” AND “single machine”) OR TITLE-ABS-KEY (“constraint programming” AND “parallel machines”) OR TITLE-ABS-KEY (“constraint programming” AND “open shop”)) AND (LIMIT-TO (DOCTYPE , “ar”)) AND (LIMIT-TO (LANGUAGE , “English”))	NA
Web of Science	((((((((((TS=(“constraint programming” AND “production scheduling”)) OR TS=(“constraint programming” AND “makespan”)) OR TS=(“constraint programming” AND “tardiness”)) OR TS=(“constraint programming” AND “flow time”)) OR TS=(“constraint programming” AND “completion time”)) OR TS=(“constraint programming” AND “lateness”)) OR TS=(“constraint programming” AND “flow shop”)) OR TS=(“constraint programming” AND “job shop”)) OR TS=(“constraint programming” AND “single machine”)) OR TS=(“constraint programming” AND “parallel machines”)) OR TS=(“constraint programming” AND “open shop”)	Document type: Article and Language: English

Table 2
Number of studies returned by each search source.

Search source	Number of articles
Scopus	239
Web of Science	208
Total articles without duplicates	276

3.4. Selection of bibliographic material

Aiming to select the bibliographic material included in the bibliometric analysis, we performed a qualitative analysis as a initial filter of the articles. Finally, we used the Methodi Ordinatio [132–134] to build an index to sort the papers. Based on the qualitative filter and the index obtained for each document, we could select the most promising references. We can observe that the Methodi Ordinatio has been widely applied to perform bibliometric analysis in several knowledge domains, such as production operations and management [135,136].

The qualitative filter is applied based on the following exclusion criteria: (i) the study is not written in English; and (ii) the problem under study is not directly related to production scheduling problems. After the qualitative filter, we sorted the remaining articles using the ordinatio method proposed by [132,133]. The method consists of sorting the articles with criteria based on the number of citations, year of publication, and the publications' impact factor (JCR). The goal is to prioritize the review of articles with relevant research impact that have a competitive mix in the mentioned criteria of citations, recent publications, and the impact of the journal in which the article was published. Eq. (1) illustrates the construction of the ordinatio index.

$$InOrdinatio = \frac{IF}{1000} + \alpha\,[10 - (ResearchYear - PublishYear)] + \sum C_i \tag{1}$$

where IF is the journal impact factor [137], the variable is divided by 1000 to have the same order of magnitude as the other criteria. α is the preference degree for the year of publication. A high value for α implies a higher weight of this factor in the multi-criteria indicator. Pagani et al. [132] recommend values between 1 and 10 in the α criterion. We used the value 10, given that the applications of CP in scheduling problems are recent. $ResearchYear$ and $PublishYear$ are the year the authors performed the bibliometric research and the article's publication year, respectively. So when the article is more than 10 years old, the time criterion scores negatively for ordinatio. Finally, $\sum C_i$ illustrates the article's total number of citations.

In summary, Fig. 1 illustrates the methodology phases applied to select articles. The framework is based on selecting the search query and the research questions, database search, result aggregation, qualitative filtering, article sorting and choice, and bibliometric and systematic analysis.

The framework phases consider first manual filtering of the articles and sorting using the Ordinatio indicator, and only then perform the bibliometric analysis. Generally, review articles capture the data using the research strings and then complete the bibliometric analysis with a specific software [132,133]. However, there is a chance that articles with no direct connection with the topic under study may be included in the bibliometric analysis, thus hindering the research. Therefore, the framework used has improved by considering the bibliometric analysis in the software only with the articles previously selected by filtering and sorting with Ordinatio, resulting in more significant information accuracy.

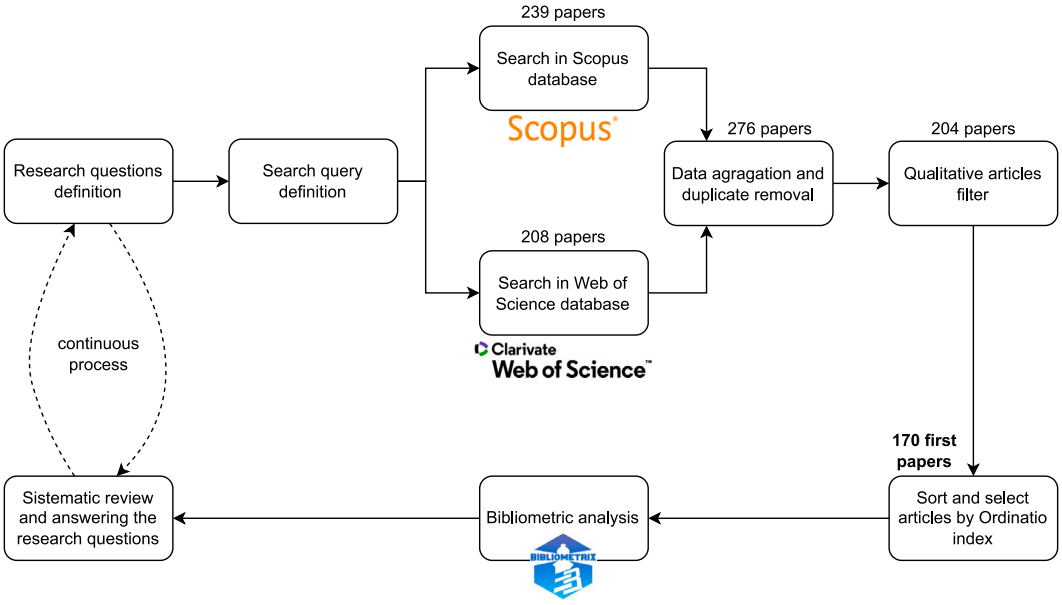

Fig. 1. Phases of the proposed methodology for the selection and review of bibliographic material.

Analyzing Fig. 1, the search with the defined query found 276 articles in the search databases, with the duplicates removed. After this process, we perform qualitative filtering, removing articles unrelated to constraint programming and production scheduling problems, totaling 204 remaining articles. Next, we applied the Ordinatio Method to choose the best articles among the criteria presented in Eq. (1). Finally, the first 170 articles were selected for the bibliometric and systematic analysis steps.

Finally, we perform the bibliometric analysis with the Bibliometrix package [10] and the systematic analysis of the articles to answer the research questions. The process is continued as we recognize the need for change in the framework and obtain new insights for future research in production scheduling with the constraint scheduling technique.

4. Bibliometric study

In this section, we present the bibliometric results of the research strings used in the search, described in Section 3.3. We describe results about the main authors, most relevant documents, networks, and conceptual structures.

4.1. Authors

One of the central issues in a bibliometric study is the determination of the authors recognized in a given research field. Fig. 2 illustrates the first ten most relevant authors with respect to the number of published documents. Analyzing this figure, we can observe that authors with the highest number of published documents are Ham A, Tasgetiren M, Abreu L, Hanzalek Z, Kandiller L, Nagano M, Gao L, Grossmann I, Prata B, Beck J, Braune R, Castro P, Edis E, Esmaelian M and Kizilay D. Ham A published eighth from 170 documents gathered in our survey, corresponding to approximately 5% of our sample. We can observe that this research topic is still at an early stage, and the publications are balanced among the researchers.

Another important matter in this scope is the distribution of published documents throughout time. Fig. 3 describes the production over time for the 15 most relevant authors. This dispersion among the publications of the most relevant authors is evidenced by this figure. Concerning the first authors in the ranking, we can highlight the following comments. The first seven authors have published his articles only in the last few years. On the other hand, Grossmann I has presented his scientific production over the course of more than one decade. With respect to the other authors, the great majority of contributions have been published from 2019 and beyond. Analyzing this figure, we can also emphasize that in the surveyed domain, except for Beck J, no other authors publishing continuously for a decade or more.

Fig. 4 illustrates the most relevant relations between the authors. Based on this figure, we can observe the formation of five clusters. The first one (in the green color) is composed by some relevant authors in the production scheduling domain, especially recognized by studies of the flow shop environment, such as QK Pan, R Ruiz, M Tasgetiren, and E Taillard. The second more dense cluster (in the red color) is based on other notorious researchers such as P Brucker, P Laborie, P Baptiste, E Vallada, and A Ham. The production environments addressed by the researchers of this cluster do not present a clear trend. The third cluster (in the purple color) is composed of other recognized researchers, such as JN Hooker. This cluster has a trend to address batch plants with applications in chemical engineering. Finally, the last two presents eleven researchers, which addressed many production environment and do not present a clear trend.

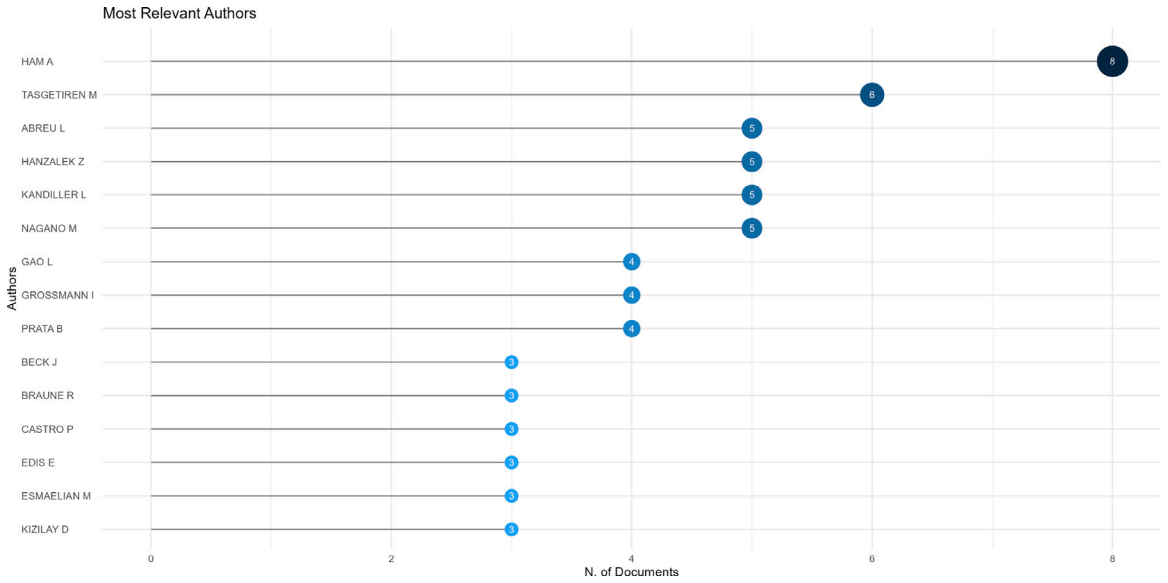

Fig. 2. The first ten most relevant authors concerning the number of documents.

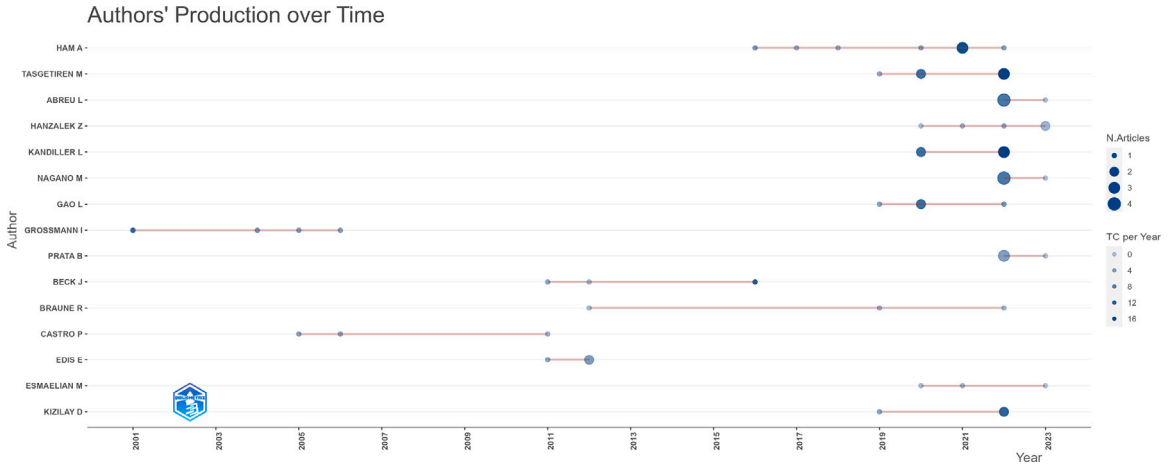

Fig. 3. Top-Authors' production over time.

Fig. 5 illustrates the geographical distribution of authors, and the opacity of the country colors represents the number of articles published. We can observe a greater concentration of publications in North America, South America, Western Europe, China, India, and Australia. Considering the production of the countries (with and without collaborations with other countries), we can observe that the United States of America, China, Turkey, Iran and France are the most productive countries (Fig. 6). Analyzing this figure, we can observe that the number of published documents by the United States of America, even considering the multiple country publications, is greater than the production of the other countries under comparison. China and Iran also have a relevant production; however, the number of publications with researchers from other countries is still limited. Finally, Turkey and Austria present an equilibrium between the publications with and without collaborations with other countries. Although these countries still do not figure among the most productive, we can highlight emerging research groups in Brazil, Mexico, Spain, India, and the United Kingdom.

With respect to the country collaboration network, we can observe four clusters, as illustrated in Fig. 7. The center of the first cluster (in orange) is the USA, aggregating China, Turkey, and other countries. The center of the second cluster (in blue) is France, followed by Canada, Iran and other countries. The center of the third cluster (in red) is Germany, agglutinating other European countries and South Africa. Finally, the last two (in purple and green) is composed by Portugal, Argentina, Tunisia, and Kuwait.

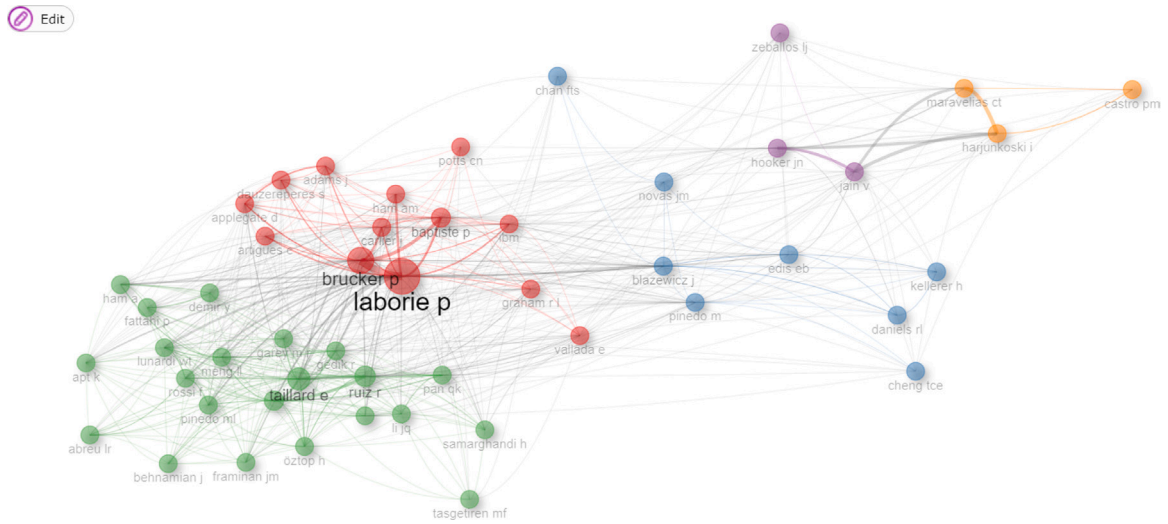

Fig. 4. Authors' net. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

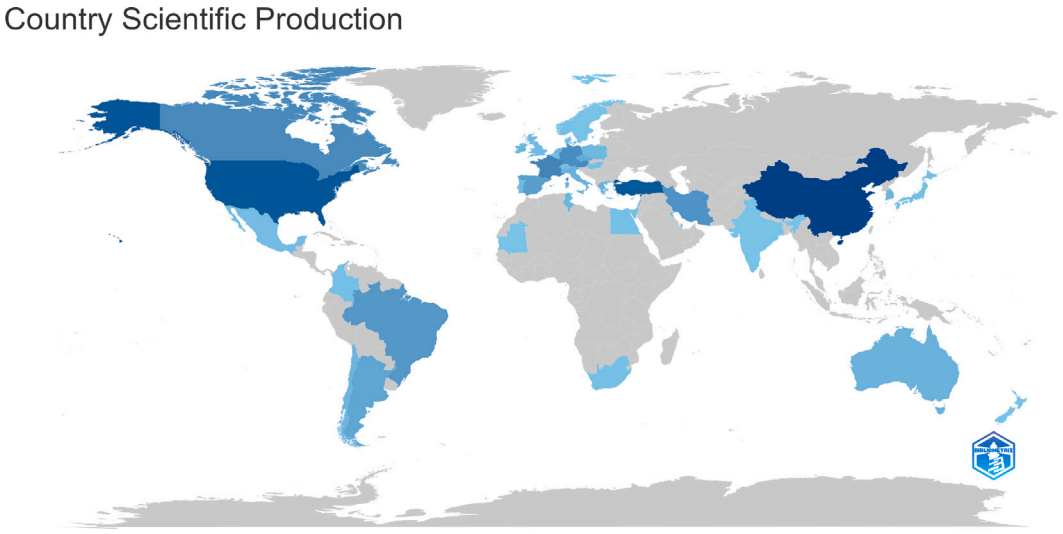

Fig. 5. Geographical distribution of publications in terms of country.

4.2. Documents

Table 3 describes the ten most cited documents. In general terms, we can emphasize the following comments. Among the first ten most cited documents, all of them were published in scientific journals. Next, we address each one of these references.

Jain and Grossmann [30] presented models and algorithms combining mixed-integer linear programming (MILP) and CP to solve the unrelated parallel machine scheduling problem. The performance measure is to minimize the processing cost of all the orders. A MILP/CP Decomposition Method is proposed as the solution procedure approach. First, a relaxed MILP model is solved, and a partial solution is found. This solution is used as a warm start for the CP model. If the solution found is feasible, it is the optimal solution. Otherwise, the machines without a feasible schedule are identified. Next, an integer cut is added for each of such machines to exclude this assignment from the feasible set. Finally, the relaxed MILP model is solved until the convergence for the optimal solution.

Hooker [33] also addressed the parallel machines scheduling problem by means of MILP and CP models. Furthermore, both models are linked via logic-based Benders decomposition. Three objective functions are minimized: cost, makespan, and total tardiness.

Ku and Beck [46] addressed the job shop scheduling problem with makespan minimization. Four MILP models are evaluated in comparison with a CP model. Concerning the small-sized test instances, MILP and CP models presented a similar performance. Nevertheless, for the large-sized instances, CP dominates the MILP models.

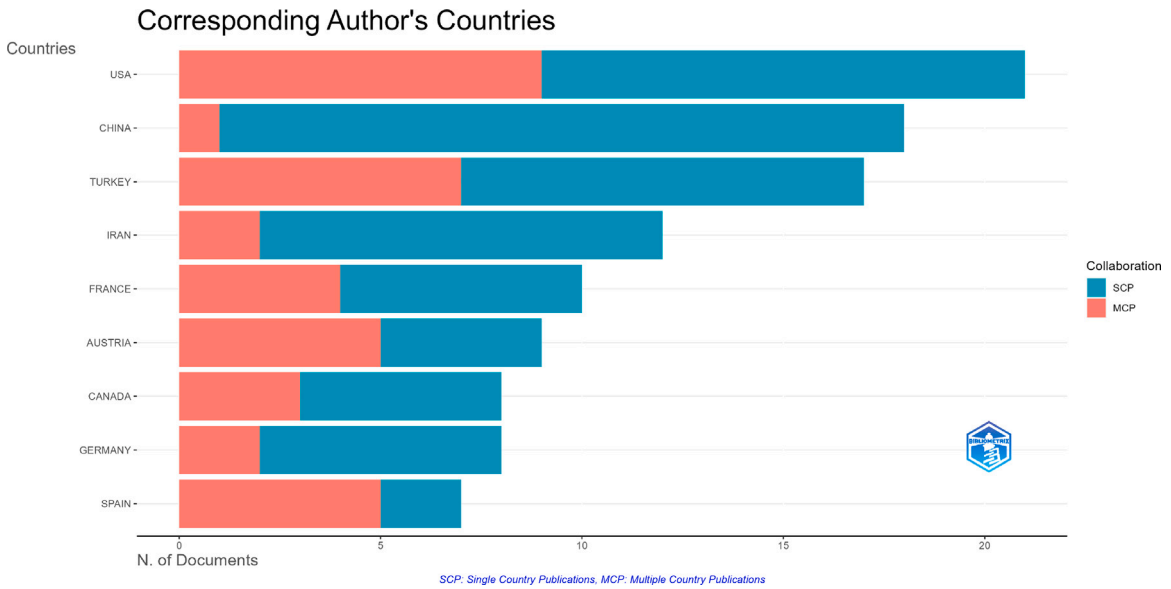

Fig. 6. The first ten most productive countries.

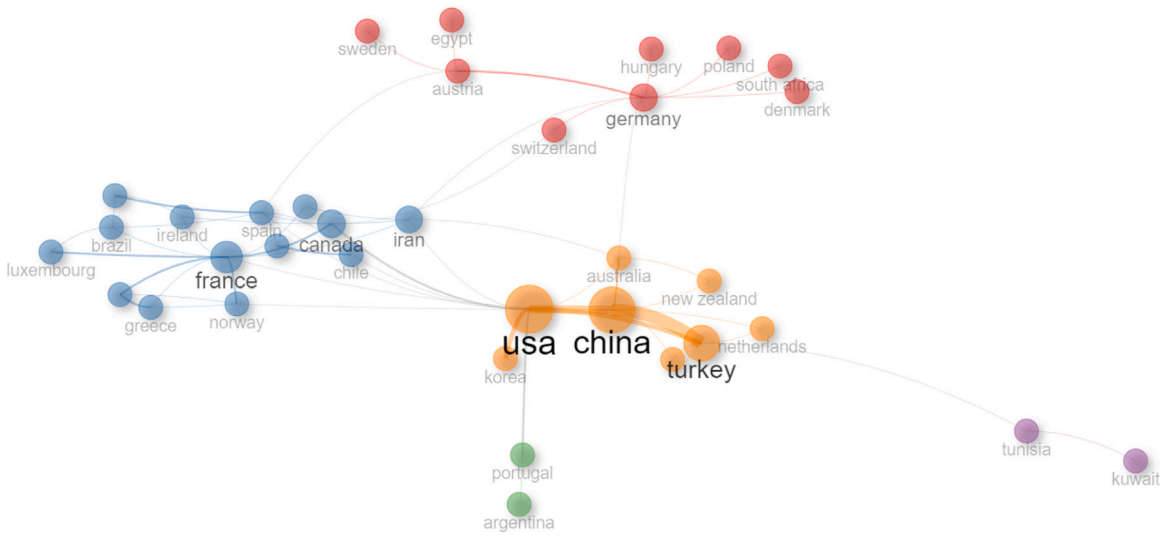

Fig. 7. Country collaboration network. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Maravelias and Grossmann [34] presented a hybrid MILP/CP decomposition algorithm for the continuous time scheduling of multipurpose batch plants. Three performance measures can be optimized: income maximization, makespan minimization, or cost minimization.

Meng et al. [93] addressed an distributed flexible job shop scheduling problem using an new CP model and four different MILP models based on four different modeling ideas. MILP and CP models prove the optimality of 62 benchmark instances. CP model obtains new best solutions for 11 benchmark instances and CP outperforms the state-of-art algorithms. In addition, CP method is very suitable for practitioners to implement and use in practice, due the simplicity of the CP formulation.

Moon and Park [48] addressed a flexible shop job production scheduling considering machine-dependent and time-dependent energy costs, energy storage, and distributed energy resources. This problem has two phases: production scheduling and energy scheduling. A hybrid algorithm combining MILP and CP models is developed as the solution procedure.

Castro and Grossmann [138] presented the Short-Term Scheduling of Multistage Batch Plants. The authors proposed a new MILP model and compares to MILP model in current literature and a CP model. The results show that the proposed MILP formulation is much more efficient with discrete-time formulations becoming preferred for larger scheduling problems where a reasonable number

Table 3
The first ten most cited documents.

Document	Authors	Year	Source	JCR (2022)	Citations
Algorithms for Hybrid MILP/CP Models for a Class of Optimization Problems	V. Jain, IE Grossmann	2001	INFORMS Journal on Computing	2.1	262
Planning and Scheduling by Logic-Based Benders Decomposition	JN Hooker	2007	Operations Research	2.7	172
Mixed Integer Programming models for job shop scheduling: A computational analysis	WY Ku, JC Beck	2016	Computers & Operations Research	4.6	104
A hybrid MILP/CP decomposition approach for the continuous time scheduling of multipurpose batch plants	CT Maravelias, IE Grossmann	2004	Computers & Chemical Engineering	4.3	101
Mixed-integer linear programming and constraint programming formulations for solving distributed flexible job shop scheduling problem	L Meng, C Zhang, Y Ren, B Zhang, C Lv	2020	Computers & Industrial Engineering	7.9	100
Smart production scheduling with time-dependent and machine-dependent electricity cost by considering distributed energy resources and energy storage	JY Moon, J Park	2014	International Journal of Production Research	9.2	92
New Continuous-Time MILP Model for the Short-Term Scheduling of Multistage Batch Plants	PM Castro, IE Grossmann	2005	Industrial & Engineering Chemistry Research	4.2	78
Integrated production and material handling scheduling using mathematical programming and constraint programming	GE Khayat, A Langevin, D Riopel	2006	European Journal of Operational Research	6.4	73
Two New Continuous-Time Models for the Scheduling of Multistage Batch Plants with Sequence Dependent Changeovers	PM Castro, IE Grossmann, AQ Novais	2006	Industrial & Engineering Chemistry Research	4.2	68
Multi-bucket optimization for integrated planning and scheduling in the perishable dairy supply chain	C Sel, B Bilgen, JM Bloemhof-Ruwaard, JGAJ van der Vorst	2015	Computers & Chemical Engineering	4.3	54

of time points are sufficient for the exact problem data. The results also show that the CP model is the best approach for makespan minimization.

El Khayat et al. [24] studied an integrated production and material handling scheduling problem, considered a job shop environment. The performance measure under consideration is the makespan minimization. Both MILP and CP models are developed as solution approaches.

Castro et al. [36] addressed the batch plant scheduling problem with sequence-dependent changeovers. Two classes of problems are considered: single-stage and multistage problems. For both cases, three objective functions are evaluated: total cost minimization, total earliness minimization, and makespan minimization. As solution procedures, MILP, CP, and hybrid MILP/CP models are developed.

Sel et al. [139] study a multi-bucket optimization for integrated planning and scheduling in the perishable dairy supply chain. The authors propose a MILP and CP formulations to integrate tactical and operational decisions efficiently and a new decomposition heuristic to improve computational efficiency. MILP and CP are combined with the heuristic to show their complementary strengths. As results, the developed hybrid approach is capable of solving real sized instances within a reasonable amount of time.

4.3. Conceptual

Fig. 8 illustrates the thematic map, aiming to provide an overview of the thematic evolution of the research involving the topic under study. Considering the quadrant in which the keywords are placed [140,141], we can classify these topics into four categories:

- Motor themes (central and developed themes): job shop scheduling, makespan, optimization, constraint programming, scheduling, mixed-integer linear programming, parallel machines scheduling, machine eligibility and evolutionary algorithms.

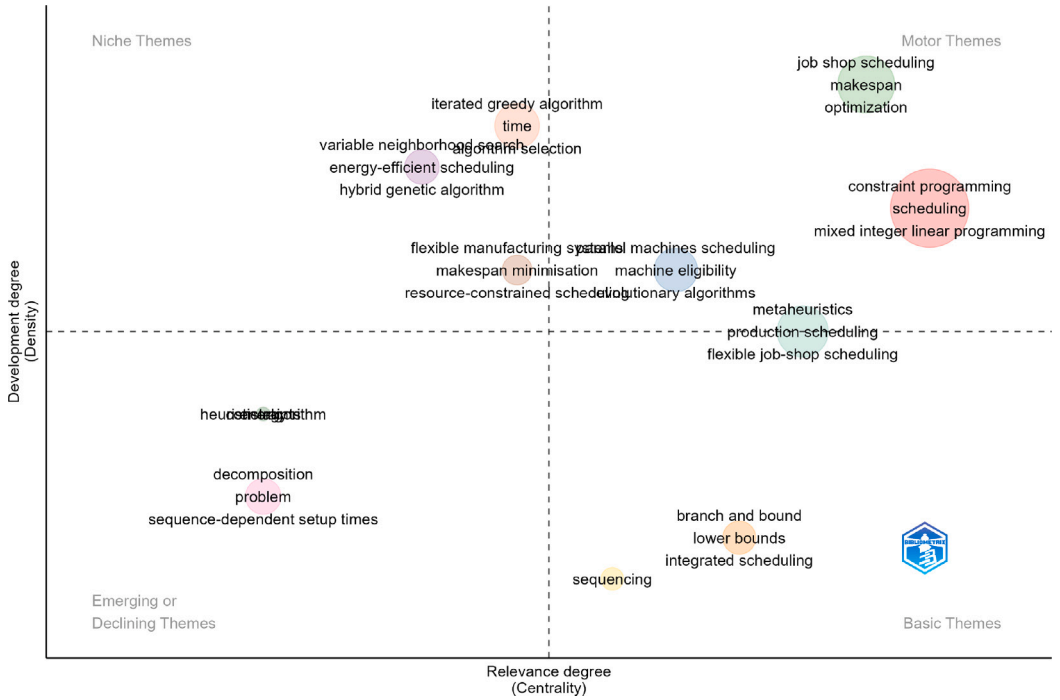

Fig. 8. Thematic map of the authors' keywords.

- Highly developed and isolated themes (peripheral and niche themes): iterated greedy algorithm, time, algorithm selection, variable neighborhood search, energy-efficient scheduling, hybrid genetic algorithm, flexible manufacturing system and resource-constrained scheduling.
- Basic and transversal terms (central and undeveloped): metaheuristics, production scheduling, flexible job-shop scheduling, branch and bound, lower bounds, integrated scheduling and sequencing.
- Emerging or declining themes (peripheral and undeveloped themes): sequence-dependent setup times, problem decomposition, constraint, heuristic algorithm.

In light of the foregoing, we can highlight the following comments. First, the job shop environment, as well as its closely related variants, is a high-developed subject of central importance. Second, the CP hybridization with heuristics, metaheuristics, or other exact methods is relatively developed. Third, the explicit consideration of sequence-dependent setup times is an emerging theme. We can observe that CP models are more efficient for production scheduling problems without additional constraints.

5. Addressing the research questions

In this section, we present the answers to the research questions described in Section 3.1 in order to satisfy the research objective of characterizing the research field under study.

5.1. Research question RQ1

Concerning the Research Question RQ1 – What are the main topics studied in research related to constraint programming and production scheduling problems? – we can emphasize the following comments. After examining the selected documents, we classified the main topics into the most addressed production environments: job shop, parallel machines, flow shop, single machine, batch scheduling, open shop, and other production environments. Table 4 illustrates the results found.

Based on the results found, we can emphasize the following comments. Job-shop-based scheduling problems are the most addressed, corresponding to a percentage of 28.49% of the occurrences. In this scope, several variants of the classical job shop, flexible job shop, multiprocessor job shop, and distributed flexible job shop can be observed. Flow-shop-based variants are in second place in this ranking. Several production environments are addressed, such as permutation flow shop, no-wait flow shop, distributed flow shop, hybrid flow shop, and distributed hybrid flow shop. Parallel machines scheduling problems are the third most production environment addressed, with 14.53% of the occurrences. Identical and unrelated parallel machines were variants addressed. Batch scheduling, single machine, and open shop problems were less studied when compared with the previously mentioned production environments. With respect to the other production scheduling problems addressed, we can highlight flexible manufacturing systems, customer order scheduling, order acceptance and scheduling, integrated planning and scheduling problems, and integrated production and distribution problems, among others.

Table 4
Most addressed production environments.

Environment	Rank	Occurrences	Percentage of the total (%)
Job shop	1	49	28.49
Flow shop	2	29	16.86
Parallel machines	3	25	14.53
Batch scheduling	4	12	6.98
Single machine	5	11	6.40
Open shop	7	9	5.23
Other environments	8	37	21.51

Table 5
Most addressed objective functions.

Indicator	Rank	Occurrences	Percentage of the total (%)
Makespan	1	91	51.70
Total tardiness	2	19	10.80
Total cost	3	15	8.52
Total weighted tardiness	5	8	4.55
Total weighted completion time	3	5	2.84
Total completion time	4	5	2.84
Earliness and tardiness	5	2	1.14
Other objective functions	6	31	17.61

Table 6
Published documents per period.

Period	Documents	Percentage of the total (%)
1990–1995	0	0.00
1996–2000	1	0.59
2001–2005	4	2.35
2006–2010	5	2.94
2011–2015	25	14.71
2016–2020	45	26.47
2021–2023	90	52.94

5.2. Research question RQ2

Concerning the Research Question RQ2 – What are the most studied objective functions? – the following comments can be highlighted. Slightly more than half of occurrences correspond to the makespan minimization as the performance measure addressed. The minimization of total tardiness, total cost, total weighted tardiness, total weighted completion time, total completion time or earliness and tardiness penalties have less than 12% of the total of objective functions. Other objective functions to be minimized are processing costs, total earliness, mean flow time, total waiting time, energy cost, overall energy consumption, total electricity cost, the total number of tardy jobs, maximal lateness, labor cost, number of setups, or net revenue. Furthermore, profit maximization is another performance measure addressed. Table 5 describes the most addresses objective functions.

5.3. Research question RQ3

Concerning the Research Question RQ3 – When and where were the documents published? – the following points must be observed. Fig. 9 illustrates the annual scientific production related to the constraint programming and production scheduling. We can observe that the number of references addressing this research topic has increased, and this increase is more significant after the year 2018. The scientific production in the year 2023 was not entirely computed since our survey was performed in October of this year. Whenever this growth trend is kept in the coming years, this research line will be one of the most relevant topics in the near future in the production scheduling domain.

Table 6 summarizes the number of published documents during the last 33 years, comprising five 5-year periods. Slightly more than 50% of the documents were published after 2021. In this context, the applications of constraint programming techniques in production scheduling problems have experienced a rapid growth process in the last few years. If this trend continues, this research line would be one of the most relevant areas in the production scheduling domain.

In accordance with Bradford's law [142], the scientific journals can be sorted in decreasing order of productivity in a given domain. Table 7 illustrates the sources that belonged to zone 1 of Bradford's law. We can observe that the first four sources published approximately one-third of the documents available in this area. Analyzing this table, we can observe the most relevant sources are high-quality journals with an impact factor greater than 6.000, except for the Computers & Operations Research. The first one is a well-known journal in the production scheduling area, and the second one is a specialized journal on the topic of Operational Research. Thereby, although such sources did not present a high impact factor, they are recognized by researchers in the above-mentioned fields.

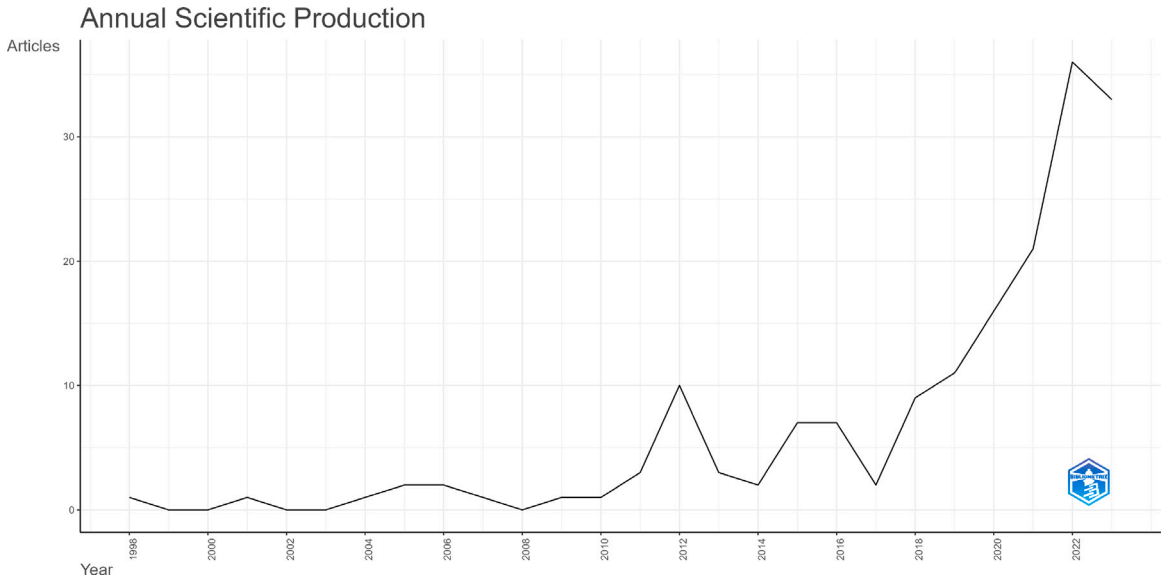

Fig. 9. Anual scientific production.

Table 7
Sources belonged to zone 1 of Bradford's law.

Source	JCR (2022)	Rank	Frequency	Acc. frequency
Computers & Industrial Engineering	7.9	1	18	18
Computers & Operations Research	4.6	2	18	36
International Journal of Production Research	9.2	3	14	50
European Journal of Operational Research	6.4	4	11	61

5.4. Research question RQ4

Concerning the Research Question RQ4 – What are the main gaps and research avenues on constraint programming in production scheduling problems? – we can address the following issues. Based on the survey performed, more research is needed in the following areas:

1. The great majority of production environments addressed are related to the job shop scheduling problem. Other variants can be better studied, such as permutation flow shop, hybrid flow shop, open shop, parallel machines, single machine, or customer order scheduling and scheduling with cumulative constraints as resource-constrained Project Scheduling or production scheduling problems with additional resource.
2. Another relevant research direction is to consider other problem characteristics and constraints, such as sequence-dependent setup times, release dates, no-wait constraints, or buffer zero constraints (machine blocking). Constraint programming techniques are more efficient for the production scheduling problems without such characteristics. In this context, further development in this field is required.
3. The vast majority of the contributions aimed to minimize the makespan. It is interesting to ensure further developments in other performance measures, such as total tardiness, earliness and tardiness penalties, or total completion time. There are several research avenues for production environments considering earliness and tardiness penalties against common due dates and windows [143]. Furthermore, more research is required to investigate constraint programming methods to solve multi-objective problems.
4. Recently, green scheduling has received special attention from operational research practitioners [144,145], and there are several opportunities in this field. Also, it is interesting to study the effect of controllable processing times [146,147] in the constraint programming techniques.
5. Another research trend is the hybridization of constraint programming and metaheuristics in the context of matheuristics [148].

6. Conclusions

6.1. Summary and main findings

This paper addresses a bibliometric analysis of the applications of CP in production scheduling problems. We conducted the bibliometric review with the Bibliometrix package using the R statistical tool. The performed review provides a better understanding of the research with the CP and production scheduling, offering possibilities for future research.

We can observe a crescent growth trend in this field, especially after 2018. In addition, the job-shop-based problems were the most addressed production environment, followed by the flow shop and parallel machines problems. With respect to the objective functions, the makespan is the most evaluated performance measure. The following journals are more influential in the field under study: CAIE, COR, IJPR, and EJOR. The most relevant authors came from the USA, China, Turkey, Iran, and France.

Based on our study, we can observe a trend of further development of CP algorithms to support the decision process in production scheduling. The provided suggestions can help the operational research practitioners to develop new theoretical results and adaptations of the existing results to other production environments.

6.2. Study limitations

We can emphasize the following study's limitations. In our study, the language coverage is limited to English. Although most of the articles are available in English, some relevant contributions can be published in other languages. In this context, some contributions could not be indexed in Scopus and Web of Science databases. Furthermore, as an inherent limitation of bibliometric research, the application of quantitative indicators sometimes cannot evaluate the research output from a given researcher.

6.3. Direction for future researches

In our opinion, the use of CP models to solve production scheduling problems will be a growing trend. Usually, the authors in this domain present computational results with mathematical programming models. Gradually, comparative analysis between mathematical programming and CP models will be incorporated. In addition, as matheuristics are a hot research topic, we believe that the hybridization of CP and heuristics and metaheuristics will be a promising research avenue in production scheduling. We applied the Methodi Ordinatio to select the bibliographic material. Although this method has been widely used in bibliometric analysis, it has some weaknesses. Future studies can consider some extensions of this index, such as the Methodi Ordinatio 2.0 [149].

Funding

This work was supported by the Brazilian National Council for Scientific and Technological Development (Conselho Nacional de Desenvolvimento Científico e Tecnológico) [Nos. 309755/2021-2, 407151/2021-4, 312585/2021-7, and 404264/2023-9] and the Brazilian Coordination for the Improvement of Higher Education Personnel (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior) [No. 001].

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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