Bibliometric study on the Heuristics simulated annealing

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Abstract. This work seeks to understand the evolution of publications on simulated Annealing heuristics through a bibliometric study and its relationship with other heuristics and methods for solving optimization problems. For this, we analyzed about 1390 metadata extracted from the Web of Science and Scopus databases, published between 1985 and December 2021, when the metadata was extracted. The results demonstrate the exponential growth of publications in the last six years, make it possible to understand the patterns of interaction with other heuristics, and may contribute to future research.

Keywords: Bibliometric analysis; Heuristics; Annealing Simulated

1 Introduction

Bibliometric analysis is a technique that aims to measure the indices of the production and propagation of scientific knowledge (Costa et al. 2021a). Bibliometrics is used mainly to identify authors of significant performance, find standards in scientific publications, and quantify the communication process efficiently. These variables influence the level of skills, resources, available time, motivation, and reputation of the individual, which are the basis of their income. Thus, the objective of this work is to present a bibliometric study of publications related to the use of Simulated Annealing heuristics, to recognize the publications of most significant relevance and the main applications for solving real problems, in addition, seeks to present the contribution of the use of this technique to solve real problems of society (Costa et al. 2022a). In addition, structuring the decision-making process, considering various aspects of evaluation at the operational and strategic levels for decision-making as seen in (do Nascimento Maêda et al. 2021; Drumond et al. 2021b; Moreira et al. 2021; Costa et al. 2022b; Da Costa et al. 2022; De Almeida et al. 2022b, a; Dos Anjos Carvalho et al. 2022; Pereira et al. 2022a, b; Rodrigues et al. 2022; Sagawe et al. 2022; LUCAS et al. 2022; Bremm De Carvalho et al. 2023; de Assis et al. 2023; dos Santos Hermogenes et al. 2023; Moreira et al. 2023; Moreıra et al. 2023; Pereira Júnior et al. 2023; Pereira et al. 2023).

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The Metaheuristic Simulated Annealing (SA) is an algorithm derived from solid annealing processes (Tenório et al. 2020), which is used for complex optimization problems. In 1983, Kirkpatrick (1983) presented the similarity between the practice of combinatorial optimization problems and large physical systems (Costa et al. 2021b). One way to explain the Simulated Annealing algorithm is by associating it with an extension of the local search method (Tabu Search), which differs from the two in that the SA can restart the local search of several initial solutions, thus making it possible to compare the best solution among those found (Costa et al. 2021b).

2 Methods

For the accomplishment of this study, the databases chosen for the selection of publications that were part of the sample were Web of Science and Scopus; their choices are based on the fact that these are widely used by students and researchers, for the preparation of research and academic papers, in addition, these databases are supported by the Bibliometrix software package R, tool used during the analysis step (Costa et al. 2021c). The choice of the package to perform the bibliometric analysis is justified by the fact that it provides the recovery of a greater variety of metadata of interest to the research, such as abstract, cited references, times cited, authors, institutions, and countries, among others, which made feasible the analyses performed (Moreira et al. 2022). It is essential to highlight that searches in these databases also locate articles published in other databases, provided that their abstracts are indexed in the Web Of Science or Scopus (de Almeida et al. 2021). This is particularly interesting for indexed journals, whose impact factor is determined by the Journal Citation Report. For the search process on the Web of Science and in the Scopus database, we used the field called topic and Article title, Abstract, Keywords and keywords plus, respectively, which comprises the occurrences of a given term(s) in the title, abstract, authors' keywords and indexes automatically generated based on the titles, which the Web of Science and Scopus creates from the original data of the work. The search terms were used: ("Simulated Annealing") AND ("*heuristic") AND ("real*") to limit the return to only publications that quoted the above expressions (do Nascimento Maêda et al. 2022).

The search for those mentioned above returned 1,984 publications, considering the period between 1985 and 2021; of this number, 647 publications are from the Web of Science and 1,337 from the Scopus database. However, to enable the analysis of the information, it was necessary to carry out the joining of the bases; for this, we used the R-tool software with the Library Bibliometrix (Jardim et al. 2022); the first necessary step was to perform the loading and transformation of the files into separate variables, one for the files extracted from the Web Of Science and the other for the data extracted from Scopus, at the end of the previous stage began the process of transforming the vectors (standard loading format) into data frames, then the margin of the bases and the removal of the duplicates were performed. The export was ended in the spreadsheet format (dos Santos and dos Santos 2022). It is essential to mention that due to the characteristic of the data, and because there are differences between the publications in each of the databases, an extra step proved necessary, for this was held a conference in

MS-Excel, using conditional formatting, for DOI column and Article title, after identifying the duplicate files, a comparison was made between the rows and was maintained to the one with the most information, at the end of the process, 1,390 publications remained (dos Santos et al. 2015). From the universe of publications in total, the articles referenced 38,178 papers (without self-citations), with an average citation per document of 20.74; in addition, the sample has approximately 765 varied sources, such as Journals, Books, etc. (Pinter et al. 2020).

Interesting information about the (CI) Collaboration Index, in Portuguese Collaboration Index representation of the Total Authors of Multiple/Total Authors of Multiple Authorship Articles (de Almeida et al. 2022) with a value of 2.52. The database analysis demonstrates the existence of 3,323 authors; considering the number of publications, we reached the coefficient of documents per author of approximately 0.42. With this, it is possible to reinforce specific authors' low concentration of publications (Maêda et al. 2021). Once the sample was initially defined, the bibliometric study of the publications was carried out, thus classifying the articles according to the year of publication, country, research area, journal, author, and several citations, using, for this, the Bibliometrics package of the R-tool, as recommended by Costa (MAÊDA et al. 2021). Also, a cloud of words was created from the most frequent terms observed in the titles of the articles and abstracts.

These results were analyzed in the light of the three primary laws of Bibliometry: i) the Bradford Law, according to which few journals concentrate most articles from a given area of knowledge; ii) Lotka's Law, which proposes that a limited number of researchers produce so much in a given area of knowledge, while a large number of researchers produce little; and iii) Zipf's Law, which, based on the principle of minimal effort, considers that the same word is used several times in a document, thus indicating his subject(Mellem et al. 2022). This type of study aims to perform relational analyses of citations, mapping the proximity, neighborhood, association, and thematic or theoretical dialogue established between authors, articles, journals, and countries, as recognized by the scientific community (Santos et al., 2022). In this stage, two methods of relational analysis of the citations were used: Collaboration Network and Collaboration WorldMap, implemented through the Bibliometrix r-tools package, enabling the construction and visualization of bibliometric networks and word cloud. As Wang (2016) proposed, collaboration networks are the "venue" for producing scientific content.

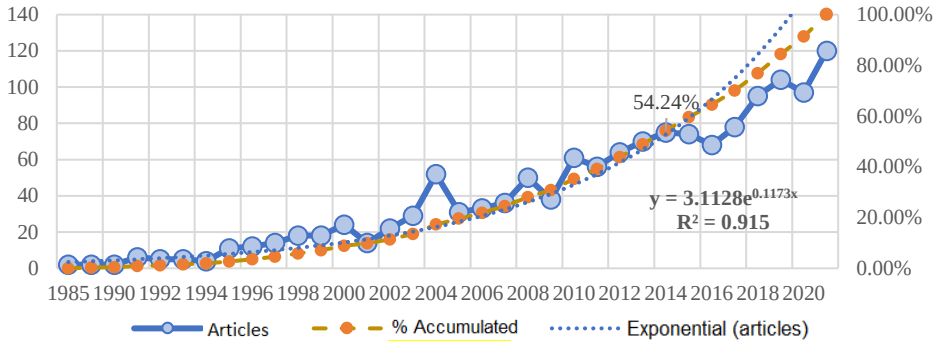
Therefore, the larger the number of references in common, the more intense the relationship line and the larger the cluster will be formed. It is interesting to demonstrate this type of analysis because it allows for categorizing and visualizing collaboration patterns in science by authors or countries (Drumond et al., 2022). The cocitation analysis measures the two articles' thematic, theoretical, and methodological proximity according to the number of publications cited simultaneously (Rocha Junior et al. 2022). Therefore, to be strongly co-cited, over the past, many authors need to cite the two articles simultaneously, thus recognizing their importance (Drumond et al. 2021a). According to the perspective of the citing community, these characteristics cause the analysis of citations to be classified as a prospective method, adequate to evidence the structure of scientific knowledge (Maêda et al., 2022).

3 Results and discussion

3.1 Bibliometric analysis of articles on Simulated Annealing

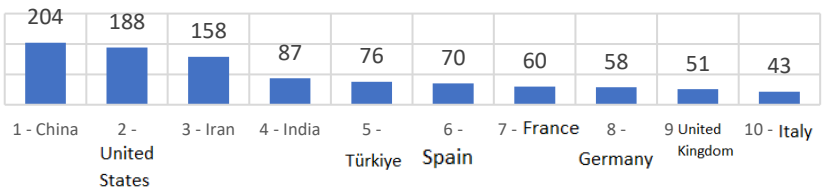
When analyzing the data, we first sought to identify fall trends or increased interest in advancing research in the following area: Simulated Annealing. In this sense, Figure 1 shows the scientific production evolution over time on the subject. It is observed that although the number of publications in 2005, 2009, 2011, and 2016 fell in previous years, there was an exponential growth in scientific production in the period analyzed. Simulated Annealing jumped from 12 articles published in 1996 to 104 in 2019. In addition, 54.24% of the articles on Simulated Annealing were published in 2014. This validates that research on Simulated Annealing is recent since approximately half of the articles on this topic have been published in the last six years.

Figure 1: Temporal evolution of the number of articles published on Simulated Annealing



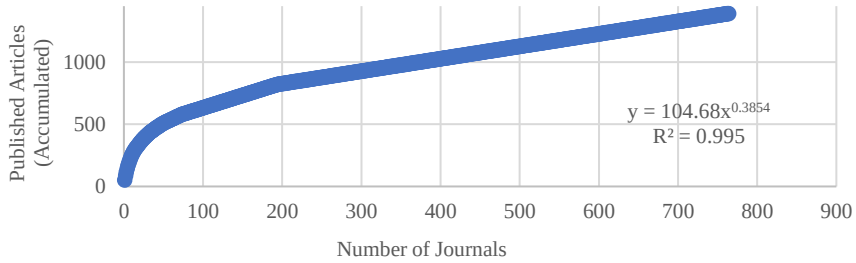
It is also concluded that the research on Simulated Annealing containing the heuristic and real terms came from several countries, 65, objectively. As illustrated in Figure 2, researchers in China led the ranking of publications by country. By publishing 204 of the 1,390 articles on Simulated Annealing containing the heuristic and absolute terms, the country surpassed the sum of the number of articles published by Germany, the United Kingdom, and Italy, which, respectively, occupied the eighth, new, and top positions in that ranking.

Figure 2: The top ten countries see research on Simulated Annealing containing the terms heuristic and real.



It was found that the 1,390 articles on Simulated Annealing containing the heuristic and real terms were published in 765 different journals, which corresponds to an average of 1.82 articles per journal. However, as suggested by Figure 3, few journals have concentrated many articles on Simulated Annealing containing the heuristic and absolute terms. In contrast, many journals have published few articles on this topic, a result consistent with the classic Bradford Law.

Figure 3: T Dispersion of articles on Simulated Annealing containing the heuristic and actual terms in the sample.



The ten journals that most published articles on Simulated Annealing containing the heuristic and real terms are shown in Table 1. Together, these journals published 250 articles, equivalent to about one-sixth of the total publications. This demonstrates that the theme has also been addressed in the leading journals of the Categories of the Web of Science and Scopus that have most emerged in terms of the number of published articles.

Table 1: The top twelve journals published on Simulated Annealing, and we have cited the above.

N	Periodic	Articles
1	Lecture Notes in Computer Science	50
2	European Journal of Operational Research	37
3	International Journal of Advanced Manufacturing Technology	28
4	International Journal of Production Research	28
5	Computers and Operations Research	24
6	Expert Systems With Applications	21
7	Computers and Industrial Engineering	18
8	Applied Soft Computing Journal	17
9	Annals of Operations Research	14
10	Advances In Intelligent Systems and Computing	13

Table 2 shows the ten articles on Simulated Annealing containing the heuristic and real terms most cited in the literature.

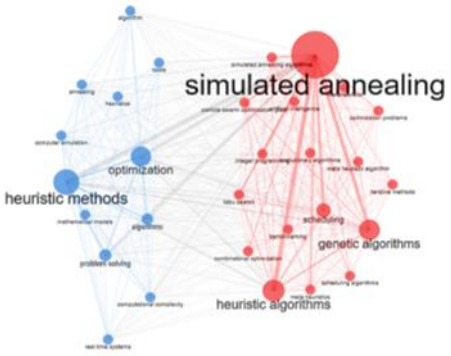
Table 2: Ten articles on Simulated Annealing containing the literature's most cited heuristic and actual terms.

N	Paper	Total Citations	TC per Year
1	YANG XS, 2010, ENG OPTIM: AN INTROD WITH METAHEURISTIC APPL	1165	97.08
2	MCMINN P, 2004, SOFTW TEST VERIF RELIAB	631	35.06
3	GAMBARDELLA LM, 1999, J OPER RES SOC	503	21.87
4	ALBA E, 2005, PARALLEL METAHEURISTICS: A NEW CLASS OF ALGORITHMS	433	25.47
5	RUTENBAR RA, 1989, IEEE CIRCUITS DEVICES MAG	422	12.79
6	SHELOKAR PS, 2004, ANAL CHIM ACTA	408	22.67
7	LOIOLA EM, 2007, EUR J OPER RES	357	23.80
8	EKREN O, 2010, APPL ENERGY	349	29.08
9	DOERNER K, 2004, ANN OPER RES	308	17.11
10	STANIFORD S, 2002, J COMPUTER SECURE	295	14.75

The most cited article, by (Yang 2010), describes the Simulated Annealing algorithm telling about its origin and application in optimization problems, its variations, and its application with Matlab and Octave. The second article, by (McMinn 2004), is presented the analysis of some articles and applications of the SA algorithm. New directions are suggested for research in each of its areas of application, in the third article by (Gambardella et al. 1999) shows that the SAH – QAP and the hybrid genetic algorithm perform better in real-world problems. The fourth article (Alba et al. 2013) discusses the meta-heuristic Simulated Annealing, presents its use in a case study, and demonstrates its variation called Parallel Simulated Annealing, in the fifth article, presents the complexities and compensations involved in a complex design problem. They are illustrated by the dissection of two very different Simulated Annealing algorithms for vlsi chip floor planning. In the sixth article, the performance of the ant colony algorithm is compared with other popular stochastic/heuristic methods: genetic algorithm, simulated annealing, and taboo search. In the seventh article of (Loiola et al. 2007), some of the essential Formulations of QAP and their classifications according to their mathematical sources are discussed. A discussion is also presented about the theoretical resources used to define lower limits for exact and heuristic algorithms; in the eighth of (Ekren and Ekren 2008), the Simulated Annealing algorithm is used to optimize the size of an integrated HYBRID PV/wind energy system with battery storage. At the end of this work, it is concluded that the SA algorithm gives a better result than the Response Surface Methodology (RSM). The ninth article by (Doerner et al. 2004) presents the Pareto Ant Colony algorithm as an effective meta-heuristic to solve the portfolio selection problem. It compares its performance with other heuristic approaches (Pareto Simulated Annealing and the Genetic Algorithm of Non-Mastered Ordering). Finally, in the tenth article, Staniford et al. (2002) use Simulated Annealing to group irregular packets into portscans using heuristics developed from actual scans, also discussing detecting other activities, such as stealth worms and Distributed Denial of Service (DDOS) control networks.

A list of the keyword Plus in the article base was established to close the bibliometric study. To provide a clearer view of the relationships, the maximum number of nodules representing the Keywords was restricted to 30, and these were used to build the network shown in Figure 4.

Figure 4: Network of sample keywords plus keywords.



In Figure 4, the size of the circles is directly proportional to the frequency of occurrence of keywords in Keywords Plus. The blue and red colors indicate the separation of clusters; it is possible to realize that the term simulated annealing has a high cooccurrence with other algorithms, such as evolutionary algorithms, taboo search, and genetic algorithms, among others; it is also possible to perceive through this cluster the association of SA with entire programming, optimization problems, scheduling, methods interactive among others. The blue cluster brings a more generic grouping, linking the main terms being heuristic methods and optimization, with generic keywords such as cost, problem-solving, computer simulation, mathematical models, etc. Finally, it is possible to see the association between the two clusters; it makes sense given that as many algorithms quoted in the red cluster as the applications, according to the literature, are part of the methods and techniques mentioned in the blue cluster.

3.2 Bibliometric analysis of articles on Simulated Annealing

After completing the previous stage, an analysis of the co-citation network of the articles on Simulated Annealing containing the heuristic and real terms was performed to understand the relationship pattern of these publications. Initially, the articles of the sample were related using the paper field to facilitate the visualization of the number of nodules that were limited to 30, and we chose to keep isolated nodules visible if they existed. Like bibliographic coupling, co-citation is also a measure of semantic similarity (Small 1973), so the analysis should be performed by evaluating that the more citations two documents have, the greater their co-citation force and the greater the chance of them being semantically related. Through Figure 4, we can perceive that

(Kirkpatrick et al. 1983) have a strong interaction with several works; this makes sense given the date of publication of the work. Given all this, there may be changes in the results, this factor is explained by the fact that the citations that the articles receive are based on the evolution of studies in the academic field, so the same can grow or maintain (Garfield 2001).

Figure 5: Network of bibliographic couplings of sample articles

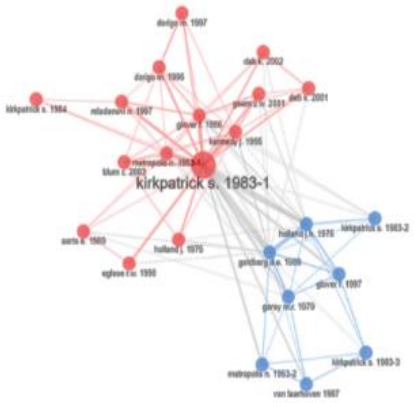


Figure 5 represents a work shared by the co-cited articles, and its size is directly proportional to the number of shares. Another point is that the smaller the distance between the articles, the greater the proximity between them, and the higher (the lower) the frequency of neighboring articles. Soon, it is noticed that there is a clear grouping around (Kirkpatrick et al. 1983).

4 Conclusion

This article presents a bibliometric study on Simulated Annealing containing the terms heuristic and real, developed from the metadata analysis of 1390 articles on the subject, published between 1985 and 2021 in journals indexed to the Wef of Science and Scopus databases. The results showed that the scientific production on Simulated Annealing containing the terms heuristic and honest had grown exponentially and is relatively recent since about half of the articles have been published in the last six years. It was also found that approximately one-sixth of these were produced by Chinese researchers. It was also found that few journals concentrated on many articles, while many published few. With 50 articles published, Lecture Notes in Computer Science topped the publication's ranking, while Professor Reza Tavakkoli-Moghaddam was the most productive author.

The most frequent words in the most recent keywords were metaheuristic, optimization, scheduling, genetic algorithm, and particle swarm optimization. Thus, it

is understood that investigating the relationship between simulated annealing and these constructs can be an exciting path for the development of future works.

It is worth noting that the results obtained in this research cannot be generalized since they were obtained from a sample of Web of Science and Scopus articles, which may contain only some of the articles published on Simulated Annealing containing the terms heuristic and real. Even so, it is understood that the goal of understanding the evolution of scientific production in Simulated Annealing containing the heuristic and absolute terms has been identified, and its tendencies and deficiencies are understood. Finally, this work can encourage the development of new research on Simulated Annealing in such a way as to contribute to advancing knowledge of the discipline of Operational Research.

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