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Metaheuristics: a comprehensive overview and classification along with bibliometric analysis

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Abstract

Research in metaheuristics for global optimization problems are currently experiencing an overload of wide range of available metaheuristic-based solution approaches. Since the commencement of the first set of classical metaheuristic algorithms namely genetic, particle swarm optimization, ant colony optimization, simulated annealing and tabu search in the early 70s to late 90s, several new advancements have been recorded with an exponential growth in the novel proposals of new generation metaheuristic algorithms. Because these algorithms are neither entirely judged based on their performance values nor according to the useful insight they may provide, but rather the attention is given to the novelty of the processes they purportedly models, these area of study will continue to periodically see the arrival of several new similar techniques in the future. However, there is an obvious reason to keep track of the progressions of these algorithms by collating their general algorithmic profiles in terms of design inspirational source, classification based on swarm or evolutionary search concept, existing variation from the original design, and application areas. In this paper, we present a relatively new taxonomic classification list of both classical and new generation sets of metaheuristic algorithms available in the literature, with the aim of providing an easily accessible collection of popular optimization tools for the global optimization research community who are at the forefront in utilizing these tools for solving complex and difficult real-world problems. Furthermore, we also examined the bibliometric analysis of this field of metaheuristic for the last 30 years.

Keywords Metaheuristics · Bibliometric · Inspirational source · Classification · Taxonomy · Application areas

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1 Introduction

Research optimization as a mathematical discipline concerns the search for either minima or maxima of functions or objective functions in terms of real-world problems, subject to given constraints. In general, optimization comprises of a wide variety of methods from operation research, artificial intelligence, computer science, and machine learning, as used to improve business processes in practically all human endeavour and industries. More so, optimization problems arise naturally in many different disciplines. For example, in engineering design, a structural engineer designing a multi-storey building must choose materials and proportions for different structural components in the building in order to have a safe structure that is as economical as possible. Similarly, in portfolio management, a portfolio manager must choose investments that generate the largest possible rate of return for its investors while keeping the risk of major losses to acceptably low levels. Optimization problem can be formulated either as a continuous or combinatorial design search space. Continuous optimization is the process of searching for maxima (or minima) of a function $f(x)$, $x = \{x_1, x_2, \ldots, x_D\} \in R^D$ subject to $g_i(x) \leq 0$, $(i = 1,2,\ldots,M)$, $h_j(x) = 0$, $(j = 1,2,\ldots,N)$, $x_{kL} \leq x_k \leq x_{kU}, (k = 1,2,\ldots,N)$, in a D-dimensional continuous search space, where g_i and h_j are the inequality and equality constraints, respectively (Abbass 2001). The terms L and U are bounds on optimization variables. For a combinatorial optimization problem, it is the process of finding the best solution for problems with discrete set of feasible solutions. Similarly, this process also involves the searching for either maximal or minimal value of an objective function f whose domain is a discrete but large configuration search space, as opposed to a D-dimensional continuous search space. Formally, a combinatorial optimization problem can be defined as a tuple (S, f, Ω), where S is usually called a search (or solution) space with $x = \{x_1, x_2, \ldots, x_n\}$ set of variables, f is the objective function to be minimized or maximized and is defined over a mapping $f : \Omega_1 \times \Omega_2 \times \cdots \times \Omega_n \mapsto R^+$, and the variable Ω is the set of constraints that have to be satisfied to obtain feasible solutions. To solve a combinatorial optimization problem the solution $s^* \in S$ with minimum objective function value needs to be determined such that $f(s^*) \leq f(s) \forall s \in S$. The solution s^* is called the globally optimal solution of the tuple (S, f, Ω) and $s^* \subset S$ is called the set of globally optimal solutions (Ezugwu et al. 2020; Weise 2009). Figure 1 below illustrates the graphical representation of an optimization problem.

There are a wide class of optimization techniques, including linear programming, quadratic programming, convex optimization, interior-point method, trust-region method, conjugate-gradient methods, evolutionary algorithms, heuristics and metaheuristics (Meyers 2009). Therefore, for solving optimization problems, a broad class of exact and heuristics approaches do exist. In addition, the revolution of the artificial intelligence era has led to the recent development of intelligent optimization techniques that are able to comfortably provide near-optimal solutions to hard and complex real-world optimization problems, which would not have been practicable using the traditional or exact optimization methods. More so, this revolution also triggered the development of several well-known natural and bio-inspired metaheuristics global optimization techniques. Therefore, this study takes a deeper look into an interesting research area of metaheuristics design, classifications and applications areas that have been reported so far from inception to date in the literature. A brief summary of the classification of global optimization methods is illustrated in Fig. 2. It is noteworthy to mention here that a concrete definition of heuristic and metaheuristic has been elusive

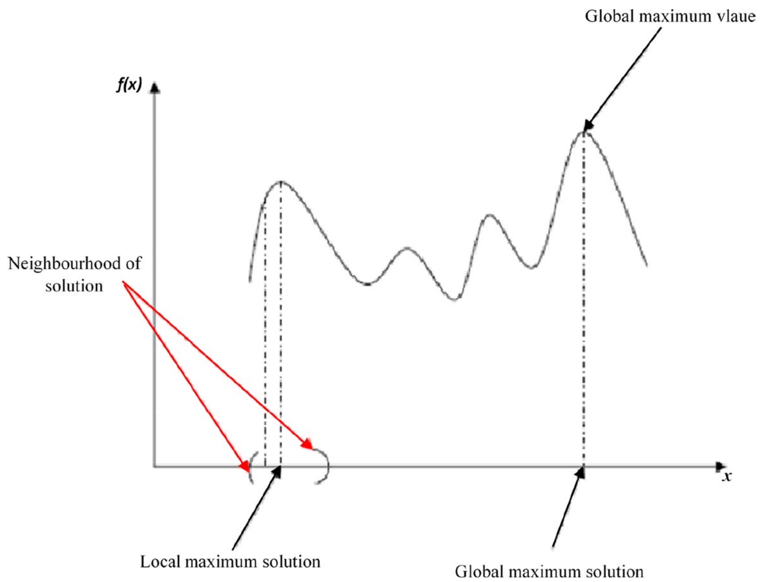

Fig. 1 An optimization problem illustration

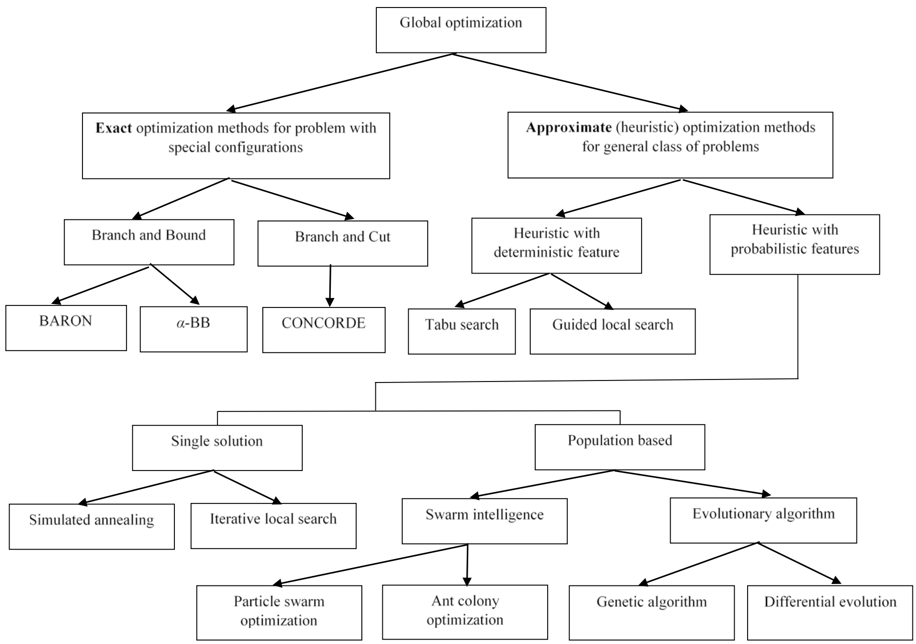

Fig. 2 A brief classification of optimization methods

and in practice, many researchers and practitioners interchange these terms. However, in a more general sense, the heuristic algorithms are known to be very specific in their search for solution and problem-dependent as well. On the other hand, the metaheuristic algorithms are high-level problem-independent techniques that can be applied to a broad range of problems.

Research in the application of nature-inspired metaheuristic algorithms has increasingly gained high popularity over the last four decades. However, there are many reasons for this popularity, which may have been strongly attributed to the successes achieved by these algorithms. In general, it is evidence to say that one of the leading reasons is that these algorithms have been inspired and designed by mimicking some of the most interesting successful phenomenon in nature (Fister et al. 2013). These natural occurring processes that have inspired the development of virtually 99% of metaheuristic algorithms can simply be classified into two namely, biological occurring process and physical laws or systems include those from chemistry and physics. It is equally interesting to note that one of the main reason why research in this area of study have continuously made progress is due to the simple fact that there are no established or well-defined mathematical principles and computational complexity analysis which present clues as to how exactly these algorithms work and interact to achieve high efficiency (Yang 2018a, b). More so, the last decade, however, has witnessed an explosive increase in the number of natural or man-made processes, that have been used as a metaphor for the development of new generation metaheuristic algorithms. However, there is an obvious desire and calls by researchers to single out those state-of-the-art metaheuristics that have long standing history of high profile performance and robustness and make them perpetual optimization tools. The principle of extracting weeds from plants can also be seen as the best possible means of minimizing the proliferation of supposedly novel metaphor-based metaheuristic algorithms that neither perform well, nor provide any useful insight.

Despite the above affirmation of acknowledging the fact that the metaheuristic research community are currently witnessing an explosive increase in the number of new algorithms being developed every day, that is not to say that the current study is taking side by recognizing only the achievements of the classical metaheuristic algorithms. In fact, there are a record number of new and novel evolutionary techniques that have been able to yielded successfully the best solutions for some hard benchmark problem instances that were initially considered to be unsolvable (Dokeroglu et al. 2019). Therefore, there is the need for a proper documentation of all the metaheuristic algorithms developed so far with the motivation to analyze, categorize and synthesize them in a meaningful manner based on their design inspirational source, useful impact and application areas.

Indeed, it is a very challenging task to present a systematic classification of all the available metaheuristic algorithm in the literature. However, few research papers have tried to present only a handful of these algorithms. For example, Fister et al. (2013) provided a brief review of nature-inspired algorithms for optimization, with about 75 list of different algorithms that were classified into two main groups, namely swarm intelligence-based algorithms and bio-inspired based algorithms. The review in Fister et al. (2013) only provided a useful insight to the aforementioned two classifications without covering the individual algorithm inspirational design sourced and application areas. Brownlee (2011) presented a well-documented reference text that describes to an extent a large number of algorithmic techniques that covers bio-inspired computation, computational intelligence and metaheuristics in a complete, consistent, and centralized manner for the research community. However, study have shown that the list of metaheuristic algorithms presented in Brownlee (2011) is quite limited or rather incomplete per say and more so, considering the fact that the study was done in 2011 for an area that have consistently evolved afterwards. Xing and Gao (2014) presented a compilation list of 134 computational intelligence algorithms, with the goal of providing to the scientific community a sense of motivation to further analyze the existing research on metaheuristic techniques for categorizing and synthesizing it in a meaningful manner. A similar more recent study was presented by Rajpurohit et al. (2017), in which a glossary of metaheuristics was provided with the authors focusing majorly on providing the core sources of inspiration for the listed algorithms. In this current study, we present a more comprehensive compilation of approximately 300 different metaheuristic algorithms with their classifications based on design inspiration, variants, useful impacts and application areas. Furthermore, the main technical contributions of this paper are summarized as follows:

- The intrinsic structure of the publications and citations count is presented as a part of bibliomteric analysis. This analysis is extended with the visual representation of the bibliographic coupling among authors, countries, institutions, and sources of publications.
- A comprehensive collation of over 200 metaheuristics algorithms starting from 1960 to 2019 with the aim of providing useful insights to some of the fundamental design concepts associated with these algorithms.
- A systematic categorization of both classical and new generation metaheuristic algorithms with emphasis on design inspirational source, variants, classification, impacts, and application areas.
- A concise presentation of a glossary of metaheuristic algorithms for easy reference by metaheuristic research enthusiasts.

The rest of the paper is organized as follows. Section 2 covers the comparative summary of the background work related to the area. In Sect. 3, we provide the refined bibliometric analysis of the area of metaheuristic. In Sect. 4, we present a discussion on some of the main inspirational source for the various algorithmic design concepts of all the well-known metaheuristic algorithms. In Sect. 5, we present a brief analysis of the useful impacts of all the metaheuristics, while in Sect. 6, we provide a comprehensive list of metaheuristic algorithms covering algorithm authors, summary of inspiration source, summary of classification, algorithm variants, impact, and application areas. Finally, Sect. 7 presents the study concluding remarks.

2 Background work on nature inspired metaheuristic algorithms

The purpose of this section is to clearly discuss the difference between the already published review on nature inspired metaheuristic algorithms and the present work. There have been attempts in the literature to comprehensively gather the metaheuristic algorithms in a single literature for easy access by researchers. For example, Fister et al. (2013) published a relatively comprehensive list of nature inspired algorithms. It covers different classes of the algorithms including swarm, bioinspired, chemistry, physics and others including sources of inspirations. Brownlee (2011) presents corpus of nature inspired algorithms covering different classes of the algorithms including stochastic, evolutionary, physical, probabilistic, swarm, immune and neural algorithms. Xing and Gao (2014) presents a rough guide to nature inspired metaheuristic algorithms. The algorithms were categorized into biology, physics, chemistry and mathematics. The core working principles and performance of each of the algorithms in the different category were presented. Sörensen (2015) traced the history of nature inspired metaheuristic algorithms in the literature. Publications or important events, application domains and paradigm shift were discussed.

Despite the efforts made by researchers to bring together a comprehensive list of the metaheuristic algorithms, only the study of Xing and Gao (2014) covered 134 metaheuristic algorithms while other attempted works covers less than 100 metaheuristic algorithms. However, over 200 nature inspired metaheuristic algorithms are scattered in the literature. The previous works mainly focuses on the core operations, applications and inspirational sources of the nature inspired metaheuristic algorithms. None of the previous works attempted bibliometric analysis of the comprehensive list of the nature inspired metaheuristic algorithms to show the impact of the algorithms in different domain despite the significance of bibliometric analysis in the literature. Table 1 presents the summary of the previous works compared to the present work.

3 Bibliometric analysis

The Bibliometrics (or Scientometrics) study is a study often performed to extract and understand the intrinsic structure of a particular research area. This type of study is available since 1969, the literal meaning of which can be found in (Pritchard 1969; Broadus 1987). Some previous notable works are (Alonso et al. 2009; Hirsch 2005; Franceschini and Maisano 2010). In recent times, bibliometric analysis has gathered a lot of attention among the researchers. Not only it provides a standalone platform for the overall growth of an area but also opens the possible scope for future studies. Moreover, young researchers can get starting point for their individual research, rather than lost in the ocean of articles.

These have been several such studies in the important research domains. More recently, Muhuri et al. (2019) studied the bibliometric aspect of Industry 4.0 and also reviewed the background work in that area. Shukla et al. (2020) provided the detailed bibliometric analysis on type-2 fuzzy sets and systems. Atanassov's intuitionistic fuzzy set was studied in this manner by Yu and Shi (2015), with the help of citation analysis. Some other crucial research areas with bibliometric studies are: real-time operating systems (Shukla et al. 2018), green supply chain (Amirbagheri et al. 2019), energy efficiency (Trianni et al. 2018) etc. Lately, there have been several journal specific studies also i.e. the bibliometric analysis on a particular journal. Some of such studies are as follows: Applied Soft Computing (Muhuri et al. 2018), Engineering Applications of Artificial Intelligence (Shukla et al. 2019), IEEE Transactions on Fuzzy Systems (Yu et al. 2017a, b), Knowledge-Based Systems (Cobo et al. 2015), Information Sciences (Yu et al. 2017a, b), European Journal of Operational Research (Laengle et al. 2017), International Journal of Intelligent Systems (Merigó et al. 2017), Neurocomputing (Janmaijaya et al. 2018), etc.

3.1 Data collection technique and document types

The bibliometric data is extracted from the Web of Science (WoS) repository. WoS is one of the widely used databases for bibliometric analysis. Scopus and Google scholar are other options available, however, due to the wide range of article indexing, they suffer from many inconsistencies and irrelevant publications. On the other hand, WoS not only is one of the largest databases for the bibliometric analysis but also contains the exclusive indexing of quality sources including SCI indexed journals and ranked international conferences. Therefore, WoS is accounted for the indexing of high-quality publications (Shukla et al. 2019; Yu et al. 2017a, b; Zavadskas et al. 2014; Merigó et al. 2017). Majority of analysis works are performed only with WoS data. We have

Table 1 Summary of the previous review on metaheuristic algorithms

References	No. of algorithms covered	Period covered	Remark
Fister et al. (2013)	74	1989–2013	Covered swarm, bioinspired, chemistry, physics and others in the taxonomy. Source of inspiration discussed
Brownlee (2011)	45	1942–2010	Covers different optimization algorithms and group into different classes
Xing and Gao (2014)	134	1972–2013	Presents core principles and performance of each algorithm. The algorithms were classified into 4: biology, chemistry, physics and mathematics
Sörensen (2015)	32	1957–2017	Present the history of metaheuristic algorithms by considering paradigm shift in addition to publications and applications
Our proposal	300	1978–2020	Create a list of over 200 metaheuristic algorithms and perform a comprehensive bibliometric analysis of the algorithms

used two of the widely used citations indexes such as: Science Citation Index Expanded (SCI-EXPANDED) and Social Sciences Citation Index (SSCI). The keyword used is "metaheuristic" and the search is performed till the end of 2019. The search year is from 1989 to 2019, making it the data comprises of 30 years. Because as the bibliometric point of view, it is to be noted that the term "metaheuristic" came into light only around mid-90′s. It may also be verified from the year of the first publication, which came in 1994 (see Fig. 1).

According to the collected data, there were total of 5163 papers published till the end of 2019. All the publications were classified into 11 categories or document types as marked by WoS. Table 2 shows the list of all document types which are as follows: Article (5018), Proceedings paper (304), Review (122), Early Access (56), Correction (7), Editorial Material (7), Meeting Abstract (7), Bibliography (1), Book chapter (1), Book Review (1), and Retracted Publications (1). The last percentage (%) column shows the contribution of each document types. Note that, there could be few document types lay under two categories. Thus, overall sum % may go above 100%.

3.2 Publications and citations: structure analysis

Here, we provide the publication and citation structure in metaheuristic research domain over the last 30 years. As can be seen from Fig. 3, the first publication which used the term metaheuristic came in 1994. The topic didn't see the light till starting four years, as there were only total of 12 publications. However, publications started to increase from 1998 (TP = 14). It reached in three numbers i.e. 100 publications in just 13 years (2006). The growth rate has then been tremendous over the years. It can be justified by the fact that in just last 4 years (2015–2019), the publication count is 52.84% (TP = 2728) of the total publications in the metaheuristic domain. The year 2019 saw the highest number of 941 publications and as per the trend year 2020 is supposed to publish more than 1000 papers.

Another trend to analyze is the citation structure of a research area. Figure 4 represents the line graph of the citation received by the papers publishing in metaheuristic domain. As seen with number of publications, there were only 12 citations of the work related to this area. After that, there's been an exponential growth in the citation count

Table 2 Document types in WoS

Document types	Total number	Percentage (%)
Article	5018	97.192
Proceedings paper	304	5.888
Review	122	2.363
Early access	56	1.085
Correction	7	0.136
Editorial material	7	0.136
Meeting abstract	7	0.136
Bibliography	1	0.019
Book chapter	1	0.019
Book review	1	0.019
Retracted publication	1	0.019

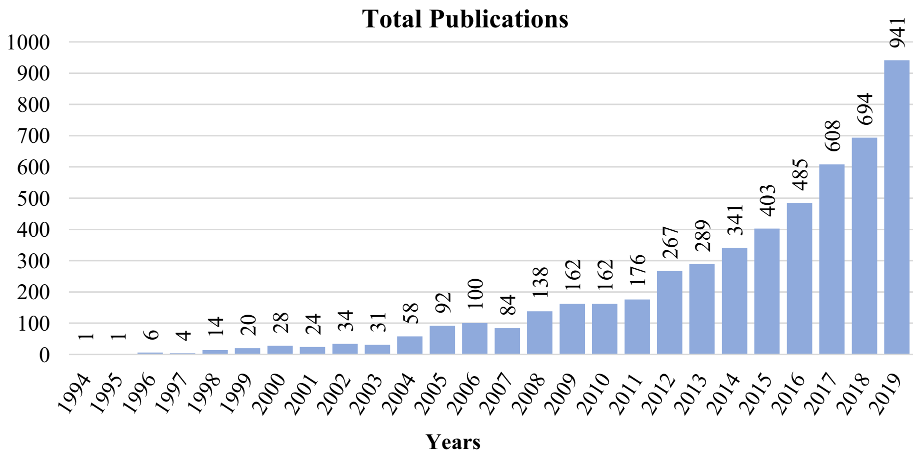

Fig. 3 Publication structure over the years in WoS

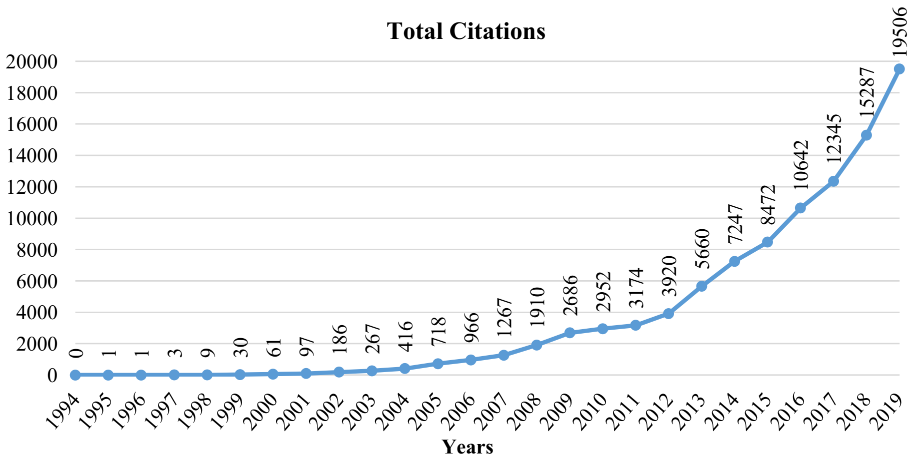

Fig. 4 Citation structure over the years, as per WoS

over the years. The highest citations of 19,506 were received in year 2019, while it is continuous four years when number of citations is more than 10,000.

3.3 VOSviewer visualization

This section is the visualization section using the widely used tool called VOSviewer. This is basically graphical mapping software used for visualizing the bibliographic network among various entities. Here, entities could be journals, organization, documents, countries, keywords etc. These entities may be inter-connected by citations, co-citations, co-authorship or bibliographic coupling. First, we have presented the bibliographic coupling among different entities. The link between the entities corresponds to the strength between them either in terms of number of publications, common references or co-citations. These entities or items may belong to a group of cluster. In the visualization, the items within a same cluster are marked with same color. The entities may be represented by the circular node and its size may vary depending on the weight of the entity.

The bibliographic coupling between the top 25 authors is shown in Fig. 5. Zandieh, Mladenovic, and Marinakis form a cluster of green color. These are the names which are visible; there are possibly other names also. This cluster implies that degree of overlap between the reference lists of publications of these authors is more. Similarly, the red color cluster of Kaveh, Yang, Deb, Coelho, Das, Soto, and Gandomi are likely working on same area (Definalty "metaheuristic") and citing the same source in their reference lists. Figure 6 shows the bibliographic coupling of the top 25 most productive countries. Here, bibliographic coupling indicates that there are more common reference list in the papers published by these countries. There are clearly two clusters, one with green color (USA, Spain, Canada, England, Germany, Italy, Brazil, Belgium, Mexico, France, Greece and Poland) and the other with Red color (China, India, Iran, Turkey, Taiwan, Australia, Malaysia, Saudi Arabia, Algeria, Egypt, Vietnam, Japan, and South Korea). The link between the China, India and Iran can be seen as thicker as compared to others. This shows the commonality and intersection of the literature work between these two countries.

The clusters in Fig. 7 shows that the Universities of Granada, Malaga, Bologna, Vienna, Laguna, Belgrade and Huazhong university of science and technology belongs to a single green cluster and most likely to have common research interest area. On the top there are two institutions from Iran viz. Shahid Beheshti University and Amirkabir University of Technology, forming a separate cluster of blue color. The biggest cluster is of red color comprising of Islamic Azad University (Iran), University of Tehran (Iran), Iran University of science and Technology (Iran), National Taiwan University of Science and Technology (Taiwan), National Institute of Technology (India), Indian Institute of Technology (India), Middlesex University (England), etc. It can be observed that three universities of

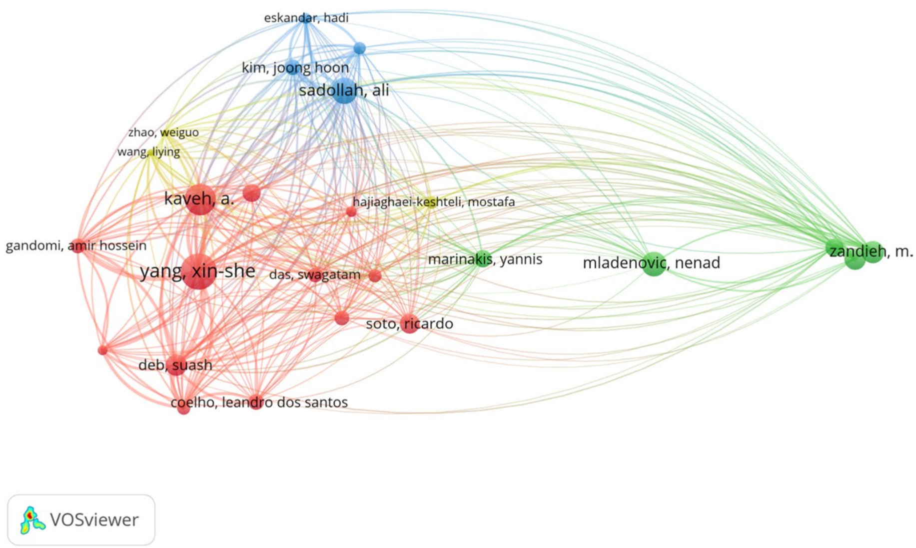

Fig. 5 Bibliographic coupling among the authors

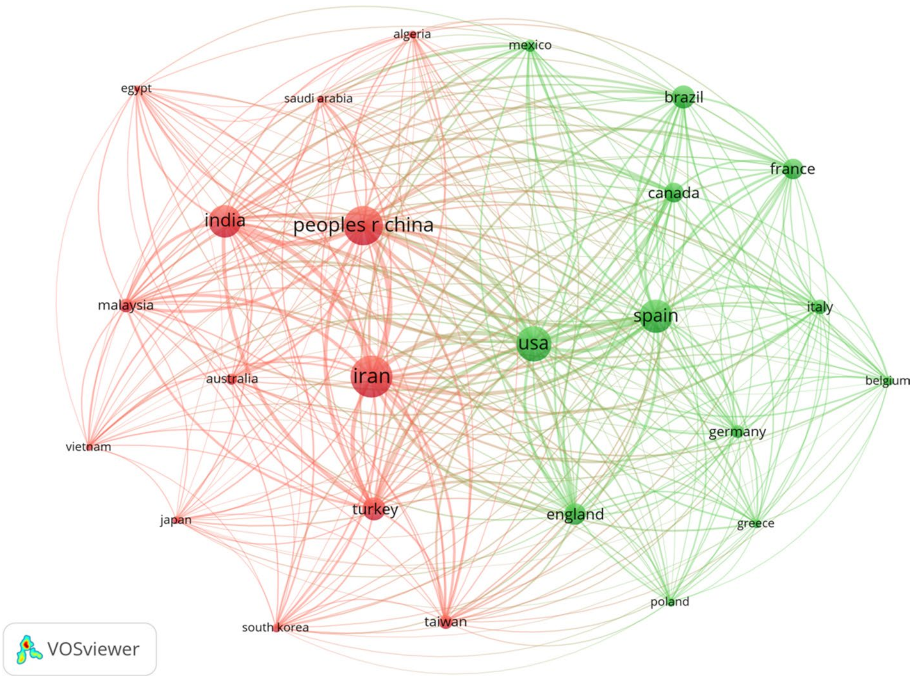

Fig. 6 Bibliographic coupling among the countries

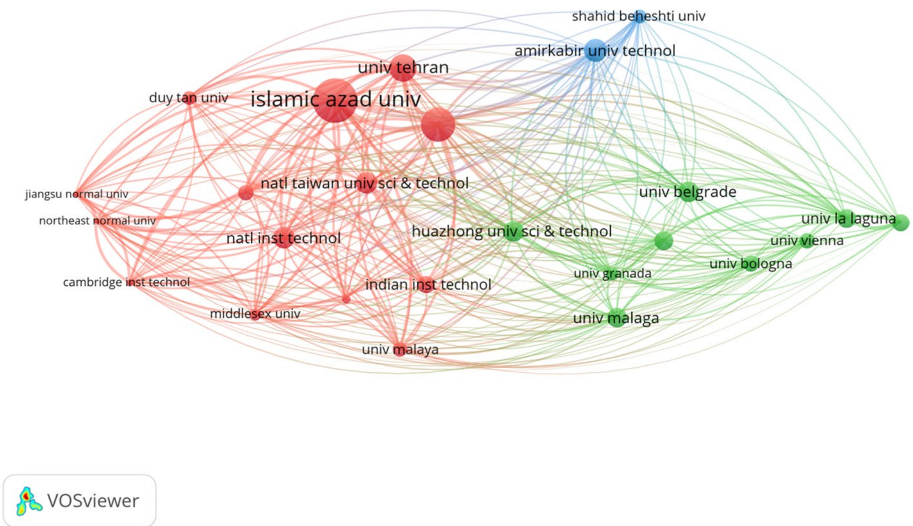

Fig. 7 Bibliographic coupling among institutions/organizations

Iran are working in meteheuristic with most similar literature background. Moreover, the underlying relationship between the authors, the countries and the institutions can be estimated with the fact that countries in the same clusters also have the authors exhibiting such behavior. For example, Swagatham Das and Yang Xin-She have together published the paper: "*Bio-inspired computation: Where we stand and what's next.*" and certainly referenced many publications which can be seen by the bibliographic coupling of their countries and institutions.

Bibliogrpahic coupling between the journals implies that the papers published in these journals have more common reference lists. Clearly there are two clusters viz. the green one (Computers and Operations Research, Computer and Industrial Engineering, Journal of Heuristics, Annals of Operations Research, and International Journal of Production) and the red one (Applied Soft Computing, Information Sciences, Neural Computing and Applications, IEEE Access, Engineering Optimization, Artificial Intelligence Review, Mathematical Problems in Engineering, Swarm and Evolutionary Optimization, Engineering Applications of Artificial Intelligence, Applied Intelligence and Turkish Journal of Electrical Engineering Computer Sciences). Pictorial representation can be seen in Fig. 8.

3.3.1 Co-author-author visualization

Here, the analysis type is co-authorship and the unit of analysis is authors. This will produce the visualization of the authors publishing together and working on similar research areas. The threshold of minimum number of papers by an author is five (5). The total of 304 authors meets the threshold among all 11,241 authors. However, the largest set of connected entities consists of only 107 authors, whose visual representation is depicted in Fig. 9a. From the figure, there are total of 15 clusters. There are maximum of 13 items in one of the cluster, although it may not be clear from the optimized version of the Fig. 9a. Thus, we have also shown that particular cluster in Fig. 9b. The connected link depicts that these authors have same paper. For example, Zeschia, Scharef, and Di Gaspero have a common publication on metaheuristic (Ceschia et al. 2011). The thickness of the link between these three authors indicates more common

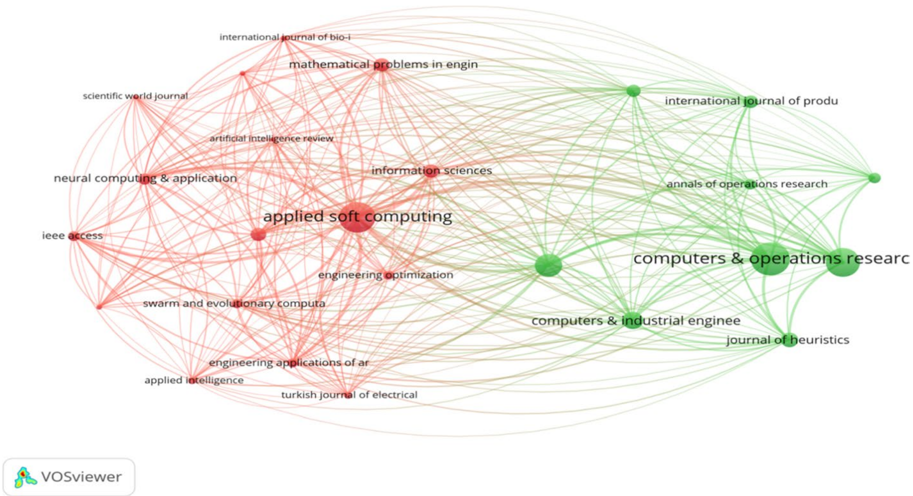

Fig. 8 Bibliographic coupling among the Journals/ Sources

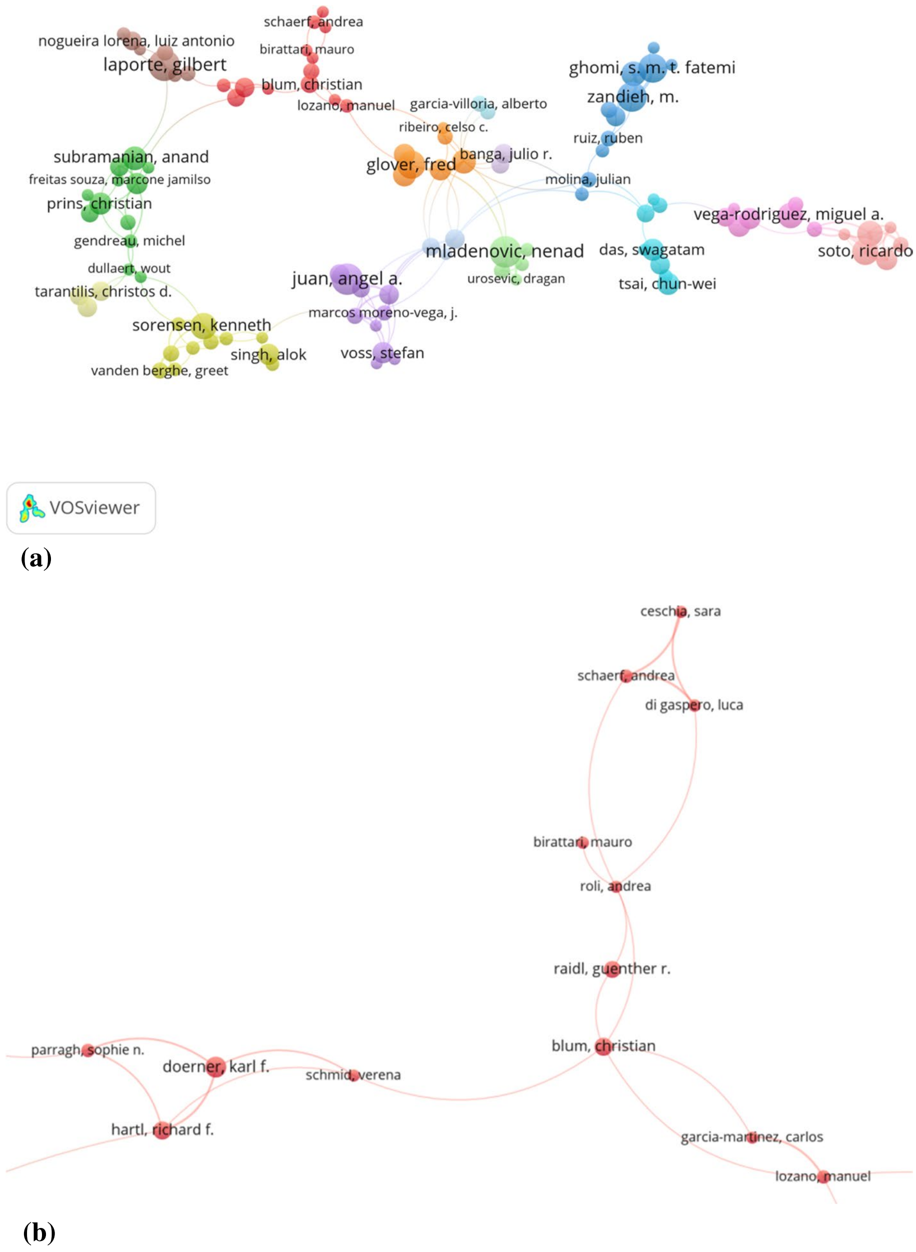

Fig. 9 **a** Co-authorship and Authors' analysis. **b** Largest cluster snippet of the Co-authorship and Authors' analysis

publications. In the overall authors (Fig. 9a), the prominent authors with bold nodes are: Subramanian, Glover, Juan, Ghomi, Mladenovic, Laporte, Das, Vega-rodriguez etc.

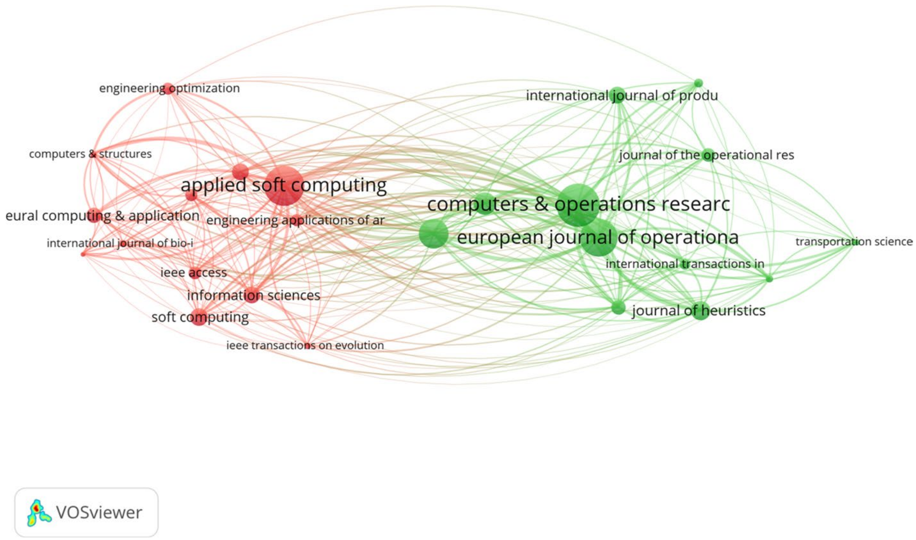

Fig. 10 Citations analysis among the journals/sources

3.3.2 Citations analysis visualization

Here, two crucial visualizations are presented with respect to the biliometric analysis. Figure 10 shows the citations analysis among the top 25 publication sources. A link between two sources (A and B) implies that the publications in source A have cited publications in Source B. The thickness and link strength signifies more number of references. From Fig. 10, two clusters can be easily visualized. In the red color cluster, Applied Soft Computing is the prominent sources, implying that the other sources in that cluster viz. engineering optimization, computers structures, IEEE access etc. have cited applied soft computing more number of times. Similarly, there are two prominent nodes in cluster 2 with green color i.e. Computers and operations research and European Journal of operational research.

Figure 11 is the citation analysis among the top 25 universities/institutions. There are 3 clusters in the visualization. Red color cluster has Islamic Azad University, Iran has the prominent node, implying that other universities in this cluster Middlesex university, Amir Kabir University, and University of Bologna have cited more papers on metaheuristic from Islamic Azad University. The other cluster is the blue color containing, National Metsovio Polythechnic, Greece, University Federal Fluminense, Brazil, Athens University of Economics and Business, Greece etc. The prominent nodes in third cluster of green colors are: University of Belgrade, Serbia, and University of La Laguna, Spain.

4 Metaheuristics inspirational source

In this day and age, full of computational challenges of ever-growing complexity there is no iota of doubt, within the research community, that behavioral patterns and phenomena observed in nature have laid the foundations of many metaheuristic algorithms (Ser et al. 2019). Virtually, all the metaheuristics designs available in the literature claimed to

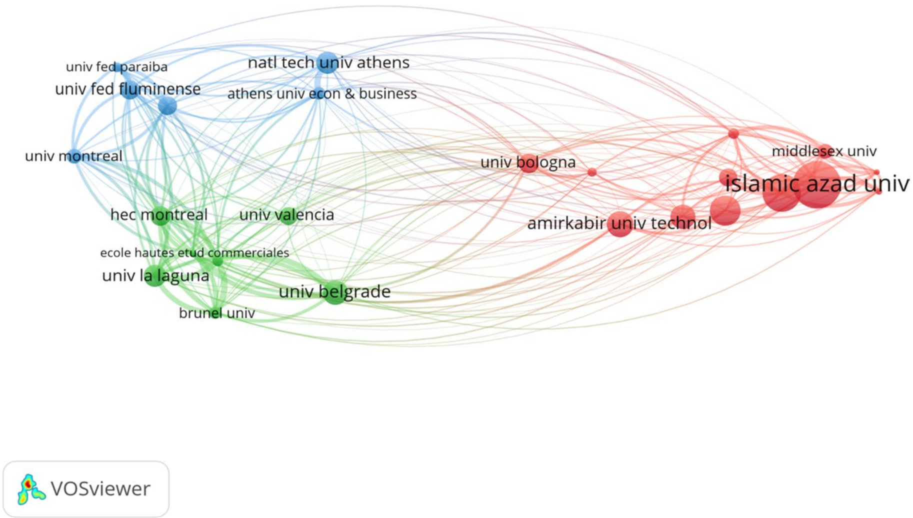

Fig. 11 Citations analysis among the institutions/universities

have been inspired by some form of natural or physical occurring phenomenon. Some of these sources of inspiration are triggered by processes emanating from biology, chemistry and physics, with the algorithmic design interactions partly or completely mimicking the respective behavioral convolutions of the aforementioned phenomenon. In recent times, many of the so-called metaheuristic algorithms have been tagged as nature-inspired, and this is because the algorithmic design concepts have been motivated by simply borrowing some sort of inspirational source from nature. Therefore, metaheuristics are often classified into sub-categories depending on the inspirational source type as mentioned earlier. For simplicity and replication purpose, we will broadly classify these metaheuristics into two main categories, namely bio-inspired and physical-inspired metaheuristics, while both falls under the generic term nature-inspired metaheuristics. Further, nature-inspired metaheuristics are a much wider class of algorithms that have been developed by drawing inspiration from nature and they are almost all population-based algorithms (Yang 2018a, b). Subsequently, we present some brief descriptions of each of the forementioned sub-classifications with carefully selected illustrative examples using few of the new proposed metaheuristics developed in 2014 and 2019 respectively.

The bio-inspired metaheuristic algorithms are more popular and common in the optimization literature, more so, these algorithms are commonly based on a metaphor of a typical biological process or interactions. These processes can range from the ecological interaction among living organisms that are pushing for survival of the fittest to the behaviors of birds in search for food source. Examples of these bio-inspired algorithms include, the symbiotic organisms search algorithm, particle swarm optimization, ant colony optimization, genetic algorithms, evolutionary algorithms, artificial bee colony, bees algorithm, firefly algorithm, invasive weed optimization, biogeography-based optimization, evolution strategy, differential evolution, shuffled frog leaping algorithm, genetic algorithm, salp swarm algorithm, harris hawks optimization, and so on. This simply means that virtually all biological processes can easily be used or translated into a metaphor for yet another new metaheuristic optimization technique and as such the listing of these algorithms becomes endless. It is noteworthy to also mention here that these algorithms on the one hand can be referred to as swarm intelligence based metaheuristic algorithms going be the concept of multiple agents in this case swarm of either bees, birds or even school of fishes collaborating to search for possible food sources or routes. Genetic algorithm, particle swarm optimization and ant colony optimization algorithms are among the early optimization methods that have attracted wide spread research interest and with recognizable industrial influence in terms of their problem solving capabilities and robustness.

In illustrating one of the bio-inspired metaheuristics techniques, we consider the symbiotic organism search, a population-based metaheuristic algorithm that was proposed in 2014 by Cheng and Prayogo (2014). This algorithm's design inspirational source was pulled from the well-known symbiotic biological relationships that most organisms often adopt for their survival in the ecosystem. Basically, there are three symbiotic relationship types namely, mutualism, commensalism and parasitism employed by organisms to enable them coexist in a very complex and dynamic environment like the ecosystem. In this case the commensalism relation denotes a situation where two living organisms benefit reciprocally. One common example of mutualism is the interaction between the Oxpecker birds and Rhinoceros. The Oxpecker lives on the rhino, sustaining itself by eating the bugs and parasites on the animal and the Rhinoceros get pest control (Ezugwu and Prayogo 2019). On the one hand, the commensalism interaction is where one of the organisms derives all the associated benefits and the coexisting organism is not affected by the immediate interaction. For example, the interaction between cattle egrets that eat the insects from the foraging activities of cattle. Lastly, when the benefit derived by one organism causes harm to another organism, the relationship is said to be a parasitism relationship. An example is the mosquitoes that rely on human blood to produce their eggs. the human (host) is affected negatively and the mosquito (parasite) benefits from the relationship. The symbiotic organism search algorithm design inspiration source is further represented using the diagram shown in Fig. 12.

The physical-inspired metaheuristics are those algorithms which inspirational design concepts were drawn from physical process that ranges from chemical reactions, music harmony and orchestra playing, water falls, sports, annealing process, black hole, physics laws, teaching and learning process, flight, politics, refraction of lights, spiral movement of galaxies to mention but a few. Some common example of these metaheuristics include, simulated annealing, black hole algorithm, tabu search, intelligent water fall algorithm, wingsuit flying search, cultural algorithm, colonial competitive algorithm, harmony search, teaching–learning-based optimization, and so on. Obviously, these sets of metaheuristic algorithms are basically driven by the principle of physical laws and complex interactions, chemical reactions and socio-economic or demographic unfolding factors. Simulated

Fig. 12 Symbiotic organism search algorithm design inspirational. *Source* from left—commensalism (Oxpeckers on a Rhinoceros back), mutualism (Cattle egrets and Cattle), and parasitism (Mosquito feeding on Human blood) (Ezugwu and Prayogo 2019)

Fig. 13 Wingsuit fly search algorithm originally inspired by the wingsuit aerodynamics flight mechanisms (Nyberg 2012)

Fig. 14 The Ludo game-based metaheuristic (Singh et al. 2019)

annealing and tabu search are among the physical-inspired based algorithms that have achieved significantly high profile industrial application throughputs.

Simply put, it is very clear that researchers in metaheuristic designs are picking up mundane ideas that are essentially found in some well-known traditionally based exact or classical mathematical optimization methods. For example, consider the most recent wingsuit search algorithm developed by mimicking the intention of a flier to land at the lowest possible point of the Earth surface within their range as illustrated in Fig. 13 (Covic and Lacevic 2020). The wingsuit fly search algorithm is a very clear illustration of an algorithm design idea that was copied from the principle of aerodynamics flight mechanisms with an already accomplished existing exact solution approaches coming from the spectrum of computational fluid dynamics (Nyberg 2012). Also consider another new metaphor-based metaheuristic algorithm called the Ludo game-based metaheuristics proposed by Singh et al. (2019). The Ludo game search algorithm claims to have drawn its inspiration from the household board game played with family, friends and kids across the globe (see Fig. 14). This algorithm in tis interactions mimics the rules of playing the game Ludo using two or four players to perform an update process for different swarm intelligent behaviors exhibited by the individual players in a row. Similarly, the algorithm uses the concepts of two and four players to enhance the exploration and exploitation of problem landscape analysis. However, taking a closer look into the design concepts of each of these new algorithms will definitely escalate the fear already highlighted by some authors in the field of metaheuristic research on the lack of originality or novelty in what is being proposed and published as new metaheuristic techniques. More so, these recent proposals are nothing short of a change in metaphor with a deceptive variation in mathematical or computational notations from the popular exact optimization methods.

Similarly, in 2020, Zhao et al. (2020) proposed yet another new metaheuristic search optimizer called the spherical search optimizer that was primarily inspired by the principle of basic hypercube search style and basic reduced hypercube search style. The algorithmic design concept and search optimization techniques of this metaheuristic can be explained as follows: consider an instance of the search process of two individuals say A and B in a three-dimensional space represented in Fig. 15 below. In order to create an initial population for the search space, two vectors (see the two blue lines on the graphs of Fig. 13) are created, which in this case denote the two individuals A and B. According to the search updating equation, the individual A searches in a cube region by a diagonal line with vertex A and B. The individual A which in this case is the original individual can walk to arbitrary position in this cube region to B using the uniform distribution model. In the cube region, B denotes the guided individual. A possible search trajectory that may be followed by the individual A is here represented by the red broken lines. It can be observed that there is no section of the broken line, which stands perpendicularly to a plane because three dimensions of A change synchronously according to the basic characteristic of the cube search style.

On a high note, the recorded advancements in the domain of global optimization, specifically in the area of metaheuristic algorithm designs have been quite interesting and probably most profitable to wide range of optimization research enthusiasts mostly in the academia. However, despite the proliferation in the manner in which these algorithms are being proposed and published on monthly basis, there have been relatively no any new signs of novelty in the design and implementation of these so-called new arrivals or new generation metaheuristic techniques. Again, notably, other than a mere change and variation in metaphor or notations, as rightly pointed out by Sörensen (2015), these metaheuristics

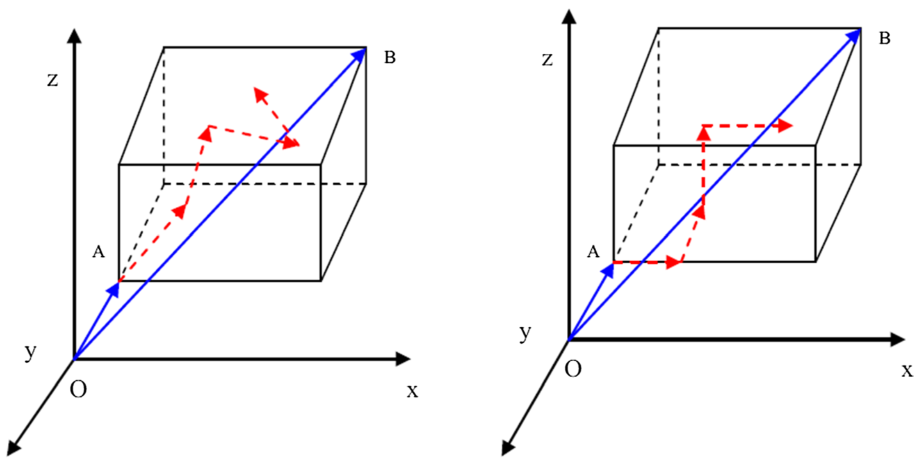

Fig. 15 On the left is the hypercube search style and on the right is the reduced hypercube search style (Zhao et al. 2020)

apparently appears to be counterproductive in producing truly pioneering research of high quality in recent times. This is equally very true since the scientific research communities have drifted and focused their attention more on popularizing the quantity of research output rather than the novelty of research contents presented by a researcher.

5 Generalized classification of metaheuristic algorithms

Metaheuristic algorithms are generalised algorithm to find solutions as close to the optimal as possible. Due to the non-deterministic in nature, the guaranty of the optimal solution is not provided. They usually follow the repeated sequence of generating or searching an efficient solution. Evidently, no single metaheuristic algorithm can satisfy the need of all the optimisation problem as explained by the no free lunch theorem by Wolpert and Macready (1997). Most of the well-known metaheuristics algorithms are nature-inspired, but few took the motivation from other processes such as physics/chemistry-based, social science, sports-based etc. Nature-inspired metaheuristic algorithms are algorithms inspired by intelligent bahaviour of natural systems. These kind of algorithms could be from biological systems (e.g. human brain, behavior of animals and plants); nature (e.g. Big bang, waterfall and gravitation); human activities (e.g. football and interior decoration). Genetic algorithm and artificial neural network are the early nature-inspired algorithms that were inspired by biological systems. The two algorithms brought a significant breakthrough in the area of artificial intelligence. These two pioneering algorithms motivated the research community to starts proposing different nature inspired metaheuristic algorithms for solving real world problems. The salient features of the nature-inspired algorithms that make them stand out from the traditional algorithms are as follows: scalability, tolerance to missing data, interpretability, flexibility, optimization capability, adaptability, accessibility and capability to solve highly none linear and complex problems. The nature inspired mate-heuristic algorithms can be classified into different classes depending on the nature and operational capabilities of the algorithms. The taxonomy of the nature inspired metaheuristic algorithms point out the class in which a specific algorithm belongs. In addition, the relationship that exist among the nature inspired metaheuristic algorithms in shown in the taxonomy for a reader to make sense of the entire spectrum of the nature inspired metaheuristic algorithms. As already discussed, the nature inspired metaheuristic algorithms in Brownlee (2011) falls into different classes as follows:

5.1 Genetic algorithms

The trend in research in the field of metaheuristics started after 1950, but one of the landmark studies which initiate the trend of work in this type of algorithm is genetic algorithm(GA) by Holland (1962). GA is one of the simplest algorithm, it includes a set of prospective solutions considered as population. New solutions are generated using genetic operators (crossover, mutation) to replace the existing solution in the population. The inspiration behind the GA is based upon the idea of Darwin's survival of the fittest.

5.2 Simulated annealing

In metallurgy, the cooling process in the furnace is used to make a metaheuristic algorithm known as simulated annealing (SA) by Kirkpatrick et al. (1983). In SA, the probability to consider the low-value solution decreases throughout the algorithm run. By doing this, the chances to get a global best increases.

> After the introduction and success of GA, SA and a few other research works for solving complex problems, researchers also started studying various natural or manmade processes to make an efficient solver. (i.e. to take the inspiration for the efficient algorithm).

5.3 Swarm intelligence

Algorithms inspired by the behaviour of a group (swarm) of organisms found in nature are called swarm optimization algorithms.

The swarm intelligence (SI) house the nature inspired metaheuristic algorithms that are inspired from group intelligent behavior of animals. Typically, the group intelligent behaviour involves collective work among the agents within a certain environment to achieve their goal such as flocks of birth, school of fish and colonies of ants. The intelligent behavior is in different organizational format aiming to solve problem which includes: distributed, self-organizing and de-centralization within the environment. Let us look at some of the common goals that such kind of collective intelligent behavior tends to achieve, for example, foraging for food, re-location of colony and evading of prey. The agent work together in harmony, information flows within the participating agents or stored or it is communicated within the environment, for example, the communication can be performed through the use of ants pheromones, fish proximity, bees dancing, etc. The typical example of the nature inspired algorithms that falls within this category includes but not limited to: Particle swarm optimization, Ant Colony Optimization algorithm, Bees algorithm and bacterial foraging. These category of algorithms are the second generation of the nature inspired algorithms that starts springing up motivated from the first generation algorithms that is the EC.

Particle swarm optimization (PSO) by Mitchell (1998) and Kennedy and Eberhart (1995), ant colony optimization (ACO) by Dorigo et al. (2006), artificial bee colony (ABC) by Karaboga (2005), firefly algorithm in Yang (2009, 2010a, b), and cuckoo search by Yang and Deb (2009), etc. are few swarm intelligence based algorithms.

Swarm intelligence is a relatively new field. The proper research on this field is started with the introduction of PSO. Earlier, there are very few studies based on the behaviour of animals for computation. In PSO, candidate solutions are treated as particles which explore the search space. The search for better solutions is guided by the local best and global best present. The change in solution toward better one is done using velocity by which a particle moves in the search space. PSO is inspired by the movement of a flock of birds or a school of fish. There is another algorithm that is based upon the ant behaviour of finding the resources(food). In ACO, artificial ants represent candidate solutions. These ants explore the search space and release pheromones. Pheromone's strength is judged by the strength of the solution. These pheromones help other ants to explore nearby areas to find a better solution. Following similar nature, another algorithm that uses bee as inspiration was proposed. In ABC, the behaviour of bees is used to scout better solutions in the search space. Firefly algorithm is another swarm intelligence based algorithm. As the name suggests, it is inspired by the firefly. The flashing ability of firefly attracts other fireflies. Each firefly is considered as a prospective solution. The brightness of flashing indicates the strength of the solution, higher the fitness of the solution gives more brightness of flashing, which results in attracting other solutions towards itself. Cuckoo search algorithm utilises the intrusive behaviour of the cuckoo laying eggs in other bird's nest. Cuckoo eggs are considered new solutions if this solution is better than the existing solution, then it may replace the existing one.

5.4 Physics and chemistry based metaheuristic approaches

The most well-known algorithm based on physics is gravitational search algorithm (GSA) by Rashedi et al. (2009). GSA is based upon the gravity and motion which basic law of physics. Like gravity, there are algorithm based upon magnetism also such as electromagnetism-like algorithm (Birbil and Fang 2003), electromagnetic field optimization by Abedinpourshotorban et al. (2016) etc. Similarly, there are algorithm inspired by chemical processes such as chemical reaction optimisation algorithm (CRO) (Lam and Li 2009) and artificial chemical reaction optimisation algorithm for global optimisation (ACROA) by Alatas (2011) etc. Both of these algorithms utilise the feature of processes going toward the equilibrium in the chemical reaction.

5.5 Social Science based metaheuristic approaches

The algorithms based on social sciences are imperialist competitive algorithm (ICA) by Atashpaz-Gargari and Lucas (2007), brainstorm optimisation algorithm (BSO) by Shi (2011) etc. ICA utilises the idea of colonies and empire. Less efficient empire is collapse, and strong survive long. The new empires are formed by invading the older weaker ones. Another well-known algorithm based on social science is BSO. BSO inspired by the ability of humans to come up with creative ideas to solve the problem.

> Not only from physics, chemistry and social sciences there are algorithms available which are inspired from varieties of processes such as sport based, water-based, music-based, math-based etc. Intelligent water drops algorithm (IWD) by Shah-Hosseini (2009), water cycle algorithm (WCA) by Eskandar et al. (2012), water evaporation optimisation (WEO) by Kaveh and Bakhshpoori (2016), water wave optimisation (WWO) by Zheng (2015) are water-based algorithms. League championship algorithm (LCA) by Kashan (2014) etc. are sport based algorithms. Sine Cosine Algorithm by Mirjalili (2016a, b) is a math-based algorithm. Harmony search by Geem et al. (2001) is music-based algorithm. Apart from these well-known algorithms, there are various metaheuristics algorithms. In addition to that, the improved versions of these algorithms are also vast in numbers.

5.6 Multi/many objective optimization approaches

These algorithms work on single objective or combined objective optimisation. But to solve the multi objective simultaneously, new extended versions of metaheuristics are immerged such as multi objective genetic algorithm (MOGA) by Murata and Ishibuchi

(1995), non-dominated sorting genetic algorithm (NSGA-II) by Deb et al. (2002), strength pareto archive algorithm (SPEA2) by Zitzler et al. (2001), multiobjective evolutionary algorithm based upon decomposition (MOEA/D) by Zhang and Li (2007) etc. In addition to multi objective optimisation there is more complex problems solving known as many objective optimisations which include more than three objectives problems. The algorithms to solve these optimisations problems are NSGA-III by Yuan et al. (2014), hypervolume-based many-objective optimization (HypE) by Bader and Zitzler (2011) etc.

NSGA-II is based upon Pareto optimality and dominance relation; it helps in differentiating solutions based upon two or more objectives. SPEA2 uses an external archive and clustering to differentiate better solution from the population. In MOEA/D, objectives are decomposed, and a reference vector is introduced to optimise multiobjective problems. MOEA/D is also an efficient procedure for many objective optimisation, but NSGA-II and SPEA2 fail with the increase in the number of objectives. Using the same reference measure used in MOEA/D, NSGA-II is extended to NSGA-III to handle many objectives. There are other procedures which use performance measure such as hypervolume by Sun et al. (2018), inverted generational distance by Ishibuchi et al. (2015) etc. to solve many objective problems.

5.7 Evolutionary computation

The evolutionary computation (EC) involved the type of nature inspired metaheuristic algorithms that falls within the reams of natural evolution processes and mechanism. The evolution is the way of selection in a natural system involving changes pioneered by Darwin for survival in environment based on fitness. In this case, the processes and mechanism of evolution is described from inception to genetic material. The evolutionary algorithms investigate the computational system that looks similar to the processes and mechanism with simplified versions that tends to achieve the effective adaptive system development. The evolutionary algorithms family produce the pioneered nature inspired metaheuristic algorithm called genetic algorithm where the initial population represent the candidate solutions to the problem and the solution space is the environment. The candidate solutions evolve through natural selection process and the candidate with the best fitness survived, as such, selected as the best solution to the problem. Other algorithms in this class of EC includes but not limited to evolutionary strategy, genetic programming and differential evolution.

5.8 Immune algorithms

The immune algorithm (IA) are the category of algorithms that derived their inspiration from natural immune system processes and mechanism to create artificial immune system. The immunity of the natural system is an agent in the natural system that tries to protect the host organism from any external intrusion from pathogens and toxic substances. The pathogens contained bacteria, viruses, parasites and pollen as microorganism. The function of the natural immunity is the detection of the intrusion of the pathogen and it is protected from harming the horst organism by eliminating the pathogen. The typical example of the IA includes but not limited to artificial immune systems, clonal selection algorithms, negative selection algorithms and immune network algorithms.

5.9 Physical algorithms

The physical algorithms (PA) are the types of nature inspired metaheuristic algorithms that are derived from the computational process and mechanism of physical systems. These type of algorithms are not biologically inspired but fit well into the mate-heuristics and computational intelligence. Therefore, the algorithms can be viewed as nature inspired metaheuristic algorithms. The physical systems that inspired such types of algorithms includes: music, metallurgy, dynamic systems that is complex, interplay between evolution and culture (e.g. avalanche). The algorithms in this category mostly stochastic algorithms with a combination of both local and global techniques of searching. The algorithms that falls in this category involves simulated annealing, extremal optimization, harmony search, memetic algorithm and cultural algorithm.

5.9.1 Search techniques

Iterated Local Search: The iterated local search is the extension of multi start search. It can be considered to have double phase approach for searching combining the greedy randomized adaptive search procedure and variable neighborhood search. *Guided Local Search algorithm*: The guided local search algorithm is global optimization algorithm that is embedded with a local search. It has been extended from the local search algorithm e.g. Hill climbing. *Tabu Search*: The Tabu search is an algorithm for the control of embedded heuristic technique. The Tabu search is the category for the larger group of derivative

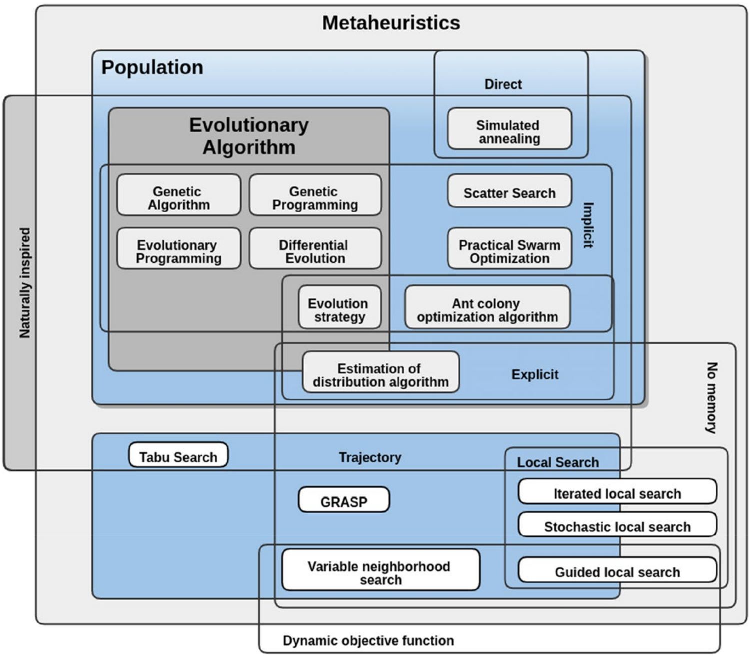

Fig. 16 Generalized classifications of metaheuristics search techniques (De Castro and Von Zuben 2000)

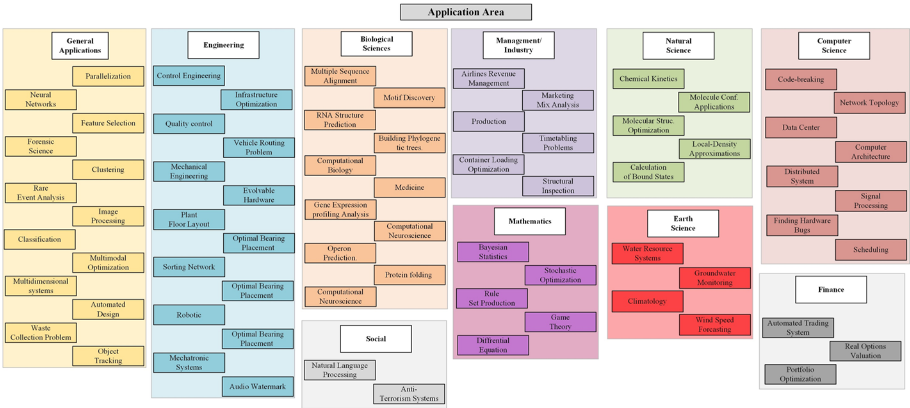

Fig. 17 Taxonomy of metaheuristics application areas

techniques that embedded metaheuristic with memory structure, example, includes reactive and parallel Tabu search.

Below there are two summary figures which depicts the generalized classifications of metaheuristics search techniques (Fig. 16) and taxonomy of metaheuristics application areas (Fig. 17). More so, the scientometrics study carried out in Sect. 3 above generally shows that there are essentially six (6) most important application areas in which several of the popular metaheuristic algorithms have been applied to solve difficult and complex problems. Theses application areas includes, engineering, biological sciences, management, factories or industry, natural sciences, and computer science, while other areas of applications that were not named in this paper are grouped under general application area category.

6 Taxonomic categorization of metaheuristic

In this section, we present in a tabular form the various categorizations of metaheuristics that have been developed so far and available in the literature. However, because metaheuristic techniques are very common and popular, they do not require much detailed introduction. The categorization provided in this space is driven by the algorithm design inspirational source, characteristics of search methods denoted as class and number of swarm or agents employed during the search process. Other factors considered for this categorization include existing variants of the algorithms and their application and citation impacts. Basically, the taxonomical categorizations of these optimization techniques are as presented in Table 3 below.

The naming convention or metaphors associated with the metaheuristics listing presented in Table 3 is taken basically from biology, physics, psychology, chemistry and surprisingly human interactions or activities. The data collected for this study also revealed that most of the metaheuristics are bio-inspired, for example, the process of natural selection, natural immune system, foraging behavior of ant colonies, parasitic behavior of cuckoo species and the Levy flight behavior of some birds and fruit flies. There are also significant number of methods adopted from physics, for example, cosmology, electricity, law of gravity and mass interactions, electromagnetics. Others includes metaphors from

Table 3 Metaheuristic algorithms sorted on the basis of impact

S. no	Algorithm	Author	Inspiration source	Class	Impact
1	Simulated annealing (1983)	Kirkpatrick et al. (1983)	Annealing in solids	Nature-inspired	45,020
2	Differential evolution (1997)	Storn and Price (1997)	Evolution	Population-based	20,661
3	Particle swarm optimization (1995)	Eberhart and Kennedy (1995)	Social behavior of bird flocking or fish schooling	Swarm-based	14,588
4	Genetic algorithm (1975)	Holland (1962)	The process of natural selection	Evolutionary-based	3433
5	Ant colony optimization (1991)	Dorigo et al. (2006)	Foraging behavior of ant colonies	Swarm-based	11,527
6	Tabu search algorithm (1986)	Glover (1986)	Tabu search	Population-based	4922
7	Artificial bee colony algorithm (2007)	Karaboga and Basturk (2007)	Intelligent foraging behavior of honey bees swarms	Swarm-based	4721
8	Harmony Search Algorithm (2001)	Geem et al. (2001)	Improvisation of music players	Nature-inspired	4594
9	Cuckoo search (2009)	Yang and Deb (2009)	Parasitic behaviour of cuckoo species and the Levy flight behaviour of some birds and fruit flies	Swarm-based	3910
10	Variable neighborhood descent algorithm (1997)	Mladenović and Hansen (1997)	Systematic change of neighborhood within a local search algorithm	Bio-inspired	3691
11	Gravitational Search Algorithm (2009)	Rashedi et al. (2009)	law of gravity and mass interactions	Nature-inspired	3441
12	Bacterial Foraging Algorithm (2002)	Passino (2002)	Foraging behavior of E. coli bacteria	Bio-inspired	2900
13	Bat algorithm (2010)	Yang (2010a, b)	Echolocation behavior of bats	Swarm-based	2842
14	Firefly algorithm (2009)	Yang (2009)	Flashing light behavior of fireflies	Swarm-based	2660
15	Grey wolves optimizer (2014)	Mirjalili et al. (2014)	Grey wolves	Bio-Inspired	2394
16	Biogeography Based Optimization (2008)	Simon (2008)	Mathematical equations that governs biogeography	Nature-inspired	2343
17	Gene Expression programming (2001)	Ferreira (2001)	Genotype/phenotype	Nature–	2212
18	Imperialist Competitive Algorithm (2007)	Atashpaz-Gargari and Lucas (2007)	Socio-politically motivated strategy	Evolutionary-based	1793
19	Teaching–learning based Optimization (2011)	Zhang et al. (2010)	The effect of influence of a teacher on learners	Population-based	1700
20	Scatter search algorithm (1977)	Glover (1977)	Several heuristics	Evolutionary-based	1688

Table 3 (continued)

S. no	Algorithm	Author	Inspiration source	Class	Impact
21	Shuffled Frog Leaping Algorithm (2003)	Eusuff and Lansey (2003)	The local search of the 'particle swarm optimization' technique; and the competitiveness mixing of information of the 'shuffled complex evolution' technique	Bio-inspired	1422
22	Covariance Matrix Adaptation–Evolution Strategy (2003)	Hansen et al. (2003)	The derandomized evolution strategy with covariance matrix adaptation	Evolutionary-based	1419
23	Shuffled complex evolution (1993)	Duan et al. (1993)	A synthesis of four concepts in global optimization	Evolutionary-based	1408
24	Clonal Selection Algorithm (2000)	De Castro and Von Zuben (2000)	Natural immune system	Bio-inspired	1317
25	The bees algorithm (2005)	Pham et al. (2005)	Foraging behavior of honey-bees	Swarm-based	1183
26	Whale Optimization Algorithm (2016)	Mirjalili and Lewis (2016)	Behavior of humpback whales	Nature-inspired	1137
27	Cultural Algorithms (1994)	Reynolds (1994)	Cultural evolution	Evolution-based	999
28	Flower pollination algorithm (2012)	Yang (2012)	Pollinating process of flowers	Bio-inspired	981
29	Invasive Weed Optimization (2006)	Mehrabian and Lucas (2006)	Colonizing weeds	Swarm-based	981
30	Great Deluge Algorithm (1993)	Dueck (1993)	Threshold accepting principle	Population-based	932
31	Krill Herd algorithm (2012)	Gandomi and Alavi (2012)	Herding behavior of krill individuals	Swarm-based	932
32	Fruit Fly Optimization Algorithm (2012)	Pan (2012)	Foraging behavior of fruit flies	Swarm-based	876
33	Big bang–big crunch (2006)	Erol and Eksin (2006)	Theory of evolution: the big bang and big crunch theory	Nature-based	830
34	Charged system search (2010)	Kaveh and Talatahari (2010)	Principles from physics and mechanics	Nature-inspired	750
35	Artificial fish swarm algorithm (2002)	Li (2002)	The collective movement of fishes and their social behaviors	swarm-based	749
36	Cuckoo optimization algorithm (2011)	Rajabioun (2011)	Egg laying and breeding attributes of cuckoo birds	Swarm-based	711
37	Ant Lion optimization (2015)	Mirjalili (2015a, b)	Hunting mechanism of antlions and tricks of ants in the traps of antlions	Swarm-based	709

Table 3 (continued)

S. no	Algorithm	Author	Inspiration source	Class	Impact
38	Moth-flame Optimization Algorithm (2015)	Mirjalili (2015a, b)	The navigation method of moths in nature called transverse orientation	Swarm-based	633
39	Group search optimizer (2006)	He et al. (2006)	Animal searching behavior	Swarm-based	587
40	Fireworks algorithm (2010)	Tan and Zhu (2010)	The sensation of fireworks explosion	swarm-based	555
41	Backtracking Search Optimization (2013)	Civicioglu (2013a, b)	Swarm intelligence	Evolutionary-based	528
42	Sine cosine algorithm (2016)	Mirjalili (2016a, b)	Sine and cosine	Nature-inspired	509
43	Dragonfly algorithm (2016)	Mirjalili (2016a, b)	Swarm behavior of dragonfly	Swarm-based	495
44	Symbiotic organisms search (2014)	Cheng and Prayogo (2014)	The symbiotic interaction strategies used by organisms to survive and transmit in the ecosystem	Swarm-based	479
45	Black Holes Algorithm (2013)	Hatamlou (2013)	Black hole phenomenon	Nature-inspired based	465
46	Water Cycle Algorithm (2012)	Eskandar et al. (2012)	Water cycle process; how rivers and streams flow to the sea	Nature-inspired	446
47	Bacteria Chemotaxis Algorithm (2002)	Muller et al. (2002)	Behavior of chemotaxis	Swarm-based	387
48	Glowworm swarm optimization (2009)	Krishnanand and Ghose (2009)	Mimics the behavior of glowworms. Glowworms carries a luminescence quantity along with them (called luciferin) and exchange information with their fellow glowworms	Swarm-based	381
49	Crow search algorithm (2016)	Askarzadeh (2016)	The intelligent behavior of crows	Swarm-based	375
50	Society and Civilization (2003)	Ray and Liew (2003)	The ability to mutually interact	Bio-inspired	372
51	Cat swarm optimization (2006)	Chu et al. (2006)	The natural behavior of cats	Swarm-based	370
52	Intelligent Water Drops Algorithm (2007)	Hosseini (2007)	Natural water drops that flow in rivers	Population-based	358
53	Multi-verse optimizer (2016)	Mirjalili et al. (2016)	Concepts in cosmology: white hole, black hole, and wormhole	Nature-inspired	358
54	Memetic Algorithm (1994)	Radcliffe and Surry (1994)	Genetic algorithm integrating local search	Evolutionary-based	346

Table 3 (continued)

S. no	Algorithm	Author	Inspiration source	Class	Impact
55	Honey-bees Mating Optimization Algorithm (2006)	Haddad et al. (2006)	Mating benavior of honey bees	Swarm-based	336
56	Salp Swarm Algorithm (2017)	Mirjalili et al. (2017)	Swarming behaviour of salps when navigating and foraging in oceans	Swarm-based	335
57	Artificial Immune System (2003)	Dasgupta et al. (2003)	Biological immune system	Bio-inspired	321
58	Differential Search Algorithm (2012)	Civicioglu (2012)	Brownian-like random-walk movement used by a moving organism	Evolutionary-based	301
59	Grasshopper Optimisation Algorithm (2017)	Saremi et al. (2017)	Behavior shown in swarms of grasshopper	swarm-based	295
60	Colliding bodies optimization (2014)	Kaveh and Mahdavi (2014)	One-dimensional collision between bodies	Population-based	293
61	Ray Optimization (2012)	Kaveh and Khayatazad (2012)	Snell's light refraction law	Nature-inspired	269
62	Social spider optimization (2013)	Cuevas et al. (2013)	The cooperative behavior of social spiders	Swarm-based	266
63	Dolphin Echolocation (2013)	Kaveh and Farhoudi (2013)	The echolocation ability of dolphins in searching for design space	Swarm-based	211
64	Monarch butterfly optimization (2019)	Wang et al. (2019)	The migration behavior of monarch butterflies	Swarm-based	203
65	Chicken swarm optimization (2014)	Meng et al. (2014)	The behavior of chickens –roosters, hens and chicks	Swarm-based	202
66	Water Wave Optimization (2015)	Zheng (2015)	The shallow water wave theory	Nature-inspired	192
67	Monkey search algorithm (2007)	Mucherino and Seref (2007)	Foraging behavior of a monkey climbing trees searching for food	Population-based	187
68	Stochastic search network (1989)	Bishop (1989)	A network of stochastic cells	Nature-inspired	186
69	Spider Monkey Optimization (2014)	Bansal et al. (2014)	Foraging behavior of spider monkeys	Swarm-based	184
70	Stochastic fractal search (2015)	Salimi (2015)	The natural phenomenon of growth	Evolutionary-based	178
71	Eagle Strategy (2010)	Yang and Deb (2010)	Combination of random search using Lévy walk with the firefly algorithm in an iterative manner	Swarm-based	171

Table 3 (continued)

S. no	Algorithm	Author	Inspiration source	Class	Impact
72	Brain Storm Optimization (2015)	Shi (2015)	Brainstorming process of human beings	Bio-inspired	170
73	Interior search algorithm (2014)	Gandomi (2014)	Ethics of aesthetic techniques usually used in interior design and decoration	Nature-inspired	167
74	Migrating Bird Optimization (2012)	Duman et al. (2012)	Flight formation of the migrating birds	Swarm-based	157
75	Animal Migration Optimization Algorithm (2014)	Li et al. (2014)	Animal migration behavior	Swarm-based	149
76	Artificial Chemical Reaction Optimization Algorithm (2011)	Alatas (2011)	Types and occurrence of chemical reactions	Nature-inspired	149
77	Lion Optimization Algorithm (2016)	Yazdani and Jolai (2016)	Special way of life of lions and their cooperation characteristics	Population-based	146
78	Queen-bee Evolution (2003)	Jung (2003)	The reproduction process of queen bees	Evolutionary-based	142
79	Wolf Search Algorithm (2012)	Tang et al. (2012)	Foraging and defense behavior of wolves	Swarm-based	129
80	Mine Blast Algorithm (2012)	Sadollah et al. (2012)	Explosion of mine bombs	Nature-inspired	125
81	Elephant herding optimization (2015)	Wang et al. (2015)	Herding behavior of elephants	Swarm-based	124
82	Fish-school Search (2008)	Bastos Filho et al. (2008)	The behaviors from fish schools	Swarm-based	123
83	Bird swarm algorithm (2016)	Meng et al. (2016)	Swarm intelligence from the social behaviour and social interaction of bird swarms	Swarm-based	117
84	Galaxy-based Search Algorithm (2011)	Shah-Hosseini (2011)	The spiral arm of spiral galaxies in searching its surrounding	Nature-inspired	115
85	Vortex Search Algorithm (2015)	Doğan and Ölmez (2015)	Vortex pattern created by the vortical flow of the stirred fluids	Nature-inspired	114
86	Earthworm Optimization Algorithm (2015)	Wang et al. (2018)	Earthworm reproduction	Swarm-based	113
87	River Formation Dynamics (2007)	Rabanal et al. (2007)	The dynamics of river formation	Nature-inspired	113
88	Lightning Search Algorithm (2015)	Shareef et al. (2015)	The lightning phenomena	Evolutionary-based	111
89	POPMUSIC algorithm (2002)	Taillard and Voss (2002)	Proximate optimality principle	–	111
90	Grenade Explosion Algorithm (2010)	Ahrari and Atai (2010)	Mechanism of grenade explosion	Nature-Inspired	110

Table 3 (continued)

S. no	Algorithm	Author	Inspiration source	Class	Impact
91	League championship algorithm (2009)	Kashan (2009)	The competition of sport teams in a sport league	Population-based	110
92	Electro-magnetism Optimization	Cuevas et al. (2012a, b)	Principle of electro-magnetism	Nature-inspired	88
93	Heat Transfer Search algorithm (2015)	Patel and Savsani (2015)	The law of thermodynamics and heat transfer	Nature-inspired	85
94	Roach Infestation Optimization (2008)	Havens et al. (2008)	Social behavior of cockroaches	Swarm-based	85
95	Artificial Cooperative Search (2013)	Civicioglu (2013a, b)	Biological interaction of two eusocial superorganisms dwelling in the same environment	Nature-inspired	83
96	Virus colony search (2016)	Li et al. (2016a, b)	Diffusion and infection approaches for the host cells adopted by virus to survive and propagate in the cell environment	Bio-inspired	83
97	Wind Driven Optimization (2010)	Bayraktar et al. (2010)	Physical equations that govern atmospheric motion	Swarm-based	83
98	Coral reefs optimization algorithm (2014)	Salcedo-Sanz et al. (2014)	Biological processes in coral reefs	Bio-inspired	79
99	Bird mating optimizer (2014)	Askarzadeh (2014)	Intelligent mating strategies of birds	Evolutionary-based	78
100	Social Cognitive Optimization (2002)	Xiao-Feng et al. (2002)	Human competition process	Population-based	78
101	Shark Smell Optimization (2014)	Abedinia et al. (2016)	The smell sense of shark and its movement to the smell source	Bio-inspired	75
102	Ions Motion Algorithm (2015)	Javidy et al. (2015)	Attraction and repulsion of anions and cations	Nature-inspired	71
103	Artificial Algae Algorithm (2015)	Uymaz et al. (2015)	Evolutionary process, adaptation process and movement of microalgae	Bio-Inspired	69
104	Optics Inspired Optimization (2015)	Kashan (2015)	Converging and diverging behaviors of concave/convex mirrors	Nature-inspired	69

Table 3 (continued)

S. no	Algorithm	Author	Inspiration source	Class	Impact
105	Water Evaporation Optimization (2016)	Kaveh and Bakhshpoori (2016)	Evaporation of a tiny amount of water molecules on a solid surface with different ability to hold contact with the solid surface	Nature-inspired	69
106	Bacterial Colony Optimization (2012)	Niu and Wang (2012)	Five typical behavior in the life cycle of E. Coli bacteria: chemotaxis, communication, elimination, reproduction, and migration	Swarm-based	67
107	Spiral dynamics inspired optimization (2011)	Tamura and Yasuda (2011)	Analogy of spiral phenomena	Nature-inspired	66
108	Tree Seed Algorithm (2015)	Kiran (2015)	Relationship amongst trees and seeds	Population-based	64
109	Rainfall optimization algorithm (2017)	Kaboli et al. (2017)	Behavior of raindrops	Nature-inspired	63
110	Exchange Market Algorithm (2014)	Ghorbani and Babaei (2014)	Trading shares on stock market	Population-based	62
111	Small-world Optimization Algorithm (2006)	Du et al. (2006)	Mechanism of small-world phenomenon	Nature-inspired	58
112	Water-flow Algorithm (2007)	Yang and Wang (2007)	The hydrological cycle in meteorology and the nature-inspired phenomenon of erosion	Nature-inspired	55
113	Plant Propagation Algorithm (2011)	Salhi and Fraga (2011)	The way the strawberry plant propagate	Bio-based	54
114	Forest optimization algorithm (2014)	Ghaemi and Feizi-Derakhshi (2014)	Trees that can survive in the forest for several decades	Evolutionary-based	53
115	Paddy field algorithm (2009)	Premaratne et al. (2009)	The reproduction of plant seeds	Bio-inspired	51
116	A Dolphin Partner Optimization (2009)	Shiqin et al. (2009)	Bionic study on dolphin	Bio-inspired	48
117	Emperor penguin optimizer (2018)	Dhiman and Kumar (2018)	The huddling manners of emperor penguins	Swarm-based	48
118	Termite colony optimization (2010)	Hedayatzadeh et al. (2010)	Intelligent behaviors of termites	Population-based	47
119	Runner-root Algorithm (2015)	Merrikh-Bayat (2015)	Runners and roots of plants in nature	Bio-inspired	46
120	Golden ball algorithm (2014)	Osaba et al. (2014)	Soccer concepts	Population-based	45

Table 3 (continued)

S. no	Algorithm	Author	Inspiration source	Class	Impact
121	Gases Brownian motion Optimization (2013)	Abdechiri et al. (2013)	Gases brownian motion and turbulent rotational motion	Evolutionary-based	43
122	Keshtel Algorithm (2014)	Hajiaghaei-Keshteli and Aminnayeri (2014)	Amazing feeding behavior of a dabbling dock, called Keshtel	Swarm-based	42
123	Locust swarm (2009)	Chen (2009a, b)	Swarm of locust	Swarm-based	42
124	Root Tree Optimization Algorithm (2016)	Labbi et al. (2016)	Root tree	Nature-inspired	42
125	Viral search (2008)	Cortés et al. (2008)	The performance of viruses	Bio-inspired	41
126	Bacterial Swarming algorithm (2007)	Tang et al. (2007)	Combination of the foraging mechanism of E. coli bacterium and swarming pattern of birds	Bio-inspired	40
127	Swallow Swarm Optimization Algorithm (2013)	Neshat et al. (2013)	Swallow swarm movement and other behavior of swallow swarm	Swarm-based	40
128	Penguins Search Optimization Algorithm (2013)	Gheraibia and Moussaoui (2013)	Collaborative hunting strategy of penguins	Swarm-based	39
129	FIFA World Cup Algorithm (2016)	Razmjooy et al. (2016)	FIFA world cup competitions	Population-based	38
130	Great Salmon Run (2012)	Mozaffari et al. (2012)	Simulation of the great salmon run	Bio-inspired	38
131	African Buffalo Optimization (2015)	Odili et al. (2015)	Organizational food searching ability of African buffalos	Swarm-based	36
132	Consultant-Guided search (2010)	Iordache (2010)	Direct exchange of information between individuals in an environment	Swarm-based	34
133	Dialectic Search (2009)	Kadioglu and Sellmann (2009)	Mental concept for local search	Bio-inspired	34
134	Japanese tree frogs calling algorithm (2012)	Hernández and Blum (2012)	calling behavior of Japanese tree frogs	Swarm-based	34
135	Sperm Whale Algorithm (2016)	Ebrahimi and Khamehchi (2016)	The lifestyle of whales	Population-based	33
136	Egyptian Vulture Optimization (2013)	Sur et al. (2013)	The foraging behavior the Egyptian Vultures	Swarm-based	31
137	Social emotional optimization algorithm (2010)	Xu et al. (2010)	Human behavior guided by emotion	Bio-based	31

Table 3 (continued)

S. no	Algorithm	Author	Inspiration source	Class	Impact
138	Butterfly Optimization Algorithm (2019)	Arora and Singh (2019)	Food search and mating behavior of butterflies	Swarm-based	30
139	Cockroach Swarm Optimization (2010)	ZhaoHui and HaiYan (2010)	The chase swarming, dispersion, and ruthless behaviour of cockroaches	Swarm-based	30
140	Elephant Search Algorithm (2015)	Deb et al. (2015)	Behavioral features of elephant herds	Swarm-based	30
141	Hierarchical Swarm Model (2010)	Chen et al. (2010)	The natural hierarchical complex system from where more complex intelligence can emerge for complex problems solving	Swarm-based	28
142	Kaizen Programming (2014)	De Melo (2014)	Concepts of continuous improvement from Kaizen Japanese methodology	Evolutionary-based	28
143	Plant Growth Optimization (2008)	Cai et al. (2008)	Plant growth theory	Bio-based	28
144	Eco-Inspired evolutionary algorithm (2011)	Parpinelli and Lopes (2011)	Ecological concepts of habitats, ecological relationships and ecological successions	Evolutionary-based	26
145	Strawberry algorithm (2014)	Merrikh-Bayat (2014)	Strawberry plant	–	25
146	Sheep Flocks Heredity Model (1999)	Nara et al. (1999)	Heredity of sheep flocks in a prairie	Evolutionary-based	24
147	Anarchic Society Optimization (2011)	Ahmadi-Javid (2011)	Disordered behavior of individuals moving towards inferior previously visited positions	Swarm-based	23
148	Human-inspired algorithms (2009)	Zhang et al. (2009)	Intelligent search strategies of mountain climbers	Population-based	23
149	Locust search (2015)	Cuevas et al. (2015)	Natural behavior of the desert locust	Swarm-based	22
150	Saplings Growing Up Algorithm (2006)	Karci and Alatas (2006)	Sowing and growing up of saplings	Swarm-based	22
151	Atmosphere Clouds Model (2013)	Yan and Hao (2013)	Spread behavior, move behavior and spread behavior of clouds in the natural world	Evolutionary-based	21

Table 3 (continued)

S. no	Algorithm	Author	Inspiration source	Class	Impact
152	Wasp swarm optimization (2005)	Pinto et al. (2005)	Interaction between individuals in the wasp colonies; the way individuals in the wasp colony interact and allocate tasks to meet the necessity of the nest	Swarm-based	20
153	Artificial Searching Swarm Algorithm (2009)	Chen (2009a, b)	Operating principle and uniform framework of bionic intelligent optimization algorithm	Swarm-based	19
154	Virus Optimization Algorithm (2016)	Liang and Cuevas Juarez (2016)	Behaviour of viruses attacking a living cell	Bio-inspired	19
155	Bacterial Evolutionary Algorithm (1996)	Numaoka (1996)	Biological phenomenon of microbial evolution	Evolutionary-based	18
156	Community of scientist optimization (2012)	Milani and Santucci (2012)	The behavior of a community of scientists	Population-based	18
157	Heart Algorithm (2014)	Hatamlou (2014)	The action of the heart and circulatory system	Bio-inspired	18
158	Bumble Bees Mating Optimization (2009)	Comellas and Martinez-Navarro (2009)	Mating behavior of bumble bees	Swarm-based	17
159	Group Counseling Optimization (2010)	Eita and Fahmy (2010)	Group counseling behavior of humans	Population-based	16
160	Magnetotactic Bacteria Optimization Algorithm (2013)	Mo and Xu (2013)	The characteristics of magnetotactic bacteria	Swarm-based	16
161	Duelist Algorithm (2016)	Biyanto et al. (2016)	Human fight	Population-based	15
162	Hunting search algorithm (2009)	Oftadeh and Mahjoob (2009)	Group hunting of animals such as lions, wolves, and dolphins	Population-based	15
163	Parliamentary Optimization Algorithm (2007)	Borji (2007)	Political competitions during parliamentary head elections	Evolutionary-based	15
164	Blind, Naked Mole-rats Algorithm (2013)	Taherdangkoo et al. (2013)	Social behaviour of the blind, naked and mole-rats in searching for food and protecting colony from invasions	swarm-based	14
165	Soccer Game Optimization (2013)	Purnomo and Wee (2013)	Soccer player movement	Evolutionary-based	14
166	Artificial swarm intelligence (2016)	Rosenberg (2016)	Biological swarms	Swarm-based	13

Table 3 (continued)

S. no	Algorithm	Author	Inspiration source	Class	Impact
167	Simplex algorithm (2007)	Pedroso (2007)	Simplex algorithm	Nature-inspired	13
168	Good Lattice Swarm Algorithm (2007)	Su et al. (2007)	Number theory and particle swarm	Swarm-based	12
169	Hydrological Cycle Algorithm (2017)	Wedyan et al. (2017)	The continuous movement of water in the natural hydrological cycle	Nature-based	12
170	Killer Whale Algorithm (2017)	Biyanto et al. (2017)	Killer whales	Swarm-based	12
171	Pity Beetle Algorithm (2018)	Kallioras et al. (2018)	Aggregation foraging behavior of the bark beetle	Swarm-based	12
172	Raven Roosting Optimization Algorithm (2016)	Brabazon et al. (2016)	The social roosting and foraging behaviour of raven bird	Swarm-based	11
173	Butterfly optimizer (2017)	Kumar et al. (2017)	Mate-location behavior of male butterflies	Swarm-based	10
174	Reincarnation algorithm (2010)	Sharma (2010)	The concept of reincarnation	Evolutionary-based	10
175	Artificial Flora Optimization Algorithm (2018)	Cheng et al. (2018)	Process of migration and movement of flora	Bio-Inspired	9
176	Invasive tumor growth optimization algorithm (2015)	Tang et al. (2015)	Tumor growth	Bio-inspired	9
177	Quantum-inspired bacterial swarming optimization (2012)	Cao and Gao (2012)	Bacterial foraging optimization	Swarm-based	9
178	Elephant swarm water search algorithm (2018)	Mandal (2018)	The water search strategy of intelligent and social elephants during drought	swarm-based	8
179	Seven-spot ladybird optimization (2013)	Wang et al. (2013)	The foraging behavior of a seven-spot ladybird	Bio-inspired	8
180	Cuttlefish Algorithm (2013)	Eesa et al. (2015)	The color changing behaviour of color cuttlefish	Bio-inspired	7
181	Jaguar algorithm (2015)	Chen et al. (2015)	The behaviors of jaguars	Swarm-based	7
182	Ring Seal Search (2016)	Saadi et al. (2016)	The natural behavior of seal pup movement	Bio-inspired	7
183	Artificial Ecosystem Algorithm (2014)	Adham and Bentley (2014)	Cooperation of different components of the ecosystem	Nature-inspired	6

Table 3 (continued)

S. no	Algorithm	Author	Inspiration source	Class	Impact
184	General Relativity Search Algorithm (2015)	Beiranvand and Rokrok (2015)	General relativity theory	Evolutionary-based	6
185	African Wild Dog Algorithm (2013)	Subramanian et al. (2013)	Communal hunting conduct of wild dogs	Swarm-based	5
186	Artificial Plant Optimization Algorithm (2011)	Cui and Cai (2013) [260]	Plant growing process	Bio-Inspired	5
187	Flying elephant algorithm (2016)	Xavier and Xavier (2016)	Generalization and interpretation of hyperbolic smoothing approach	Bio-inspired	5
188	Root Growth Optimizer (2015)	He et al. (2015)	The adaptive growth behaviors of plant roots	Bio-inspired	5
189	Central force optimization (2007)	Formato (2007)	The metaphor of gravitational kinematics	Nature-inspired	4
190	Hoopoe Heuristic Optimization (2012)	El-Dosuky et al. (2012)	The lifestyle of a bird family called hoopoe	Swarm-based	4
191	Multi-bjective Optimization Algorithms Based on sperm Fertilization Procedure (2018)	Shehadeh et al. (2018a, b)	Sperm Fertilization Procedure	Bio-inspired	4
192	The scientific algorithms (2014)	Felipe et al. (2014)	The act of researching that comprises thinking, knowledge sharing and disclosing new ideas	Nature-inspired	4
193	Camel herd algorithm (2017)	Al-Obaidi and Abdulllah (2017)	The behavior of camels in the wild	Swarm-based	3
194	Sperm Swarm Optimization Algorithm (2018)	Shehadeh et al. (2018a, b)	Sperm motility to fertilize the egg	Bio-inspired	3
195	Team Game Algorithm (2018)	Mahmoodabadi et al. (2018)	Team games	Evolutionary-based	3
196	Emperor Penguins Colony (2019)	Harifi et al. (2019)	The body heat radiation of penguins and their spiral-like movement in their colony	swarm-based	2
197	Worm Optimization (2014)	Arnaout (2014)	Foraging behaviors of Worms	Swarm-based	2
198	Bull Optimization Algorithm (2015)	Findik (2015)	Genetic operators such as crossover and mutation	Evolutionary-based	1

Table 3 (continued)

S. no	Algorithm	Author	Inspiration source	Class	Impact
199	Intelligent gravitational search algorithm (2012)	Askari and Zahiri (2012)	The phenomenon of mass interactions that is based on law of motion and Newtonian law of gravity	Nature-inspired	1
200	Sperm Motility Algorithm (2017)	Raouf and Hezam (2017)	Fertilization process in human beings	Bio-inspired	1
201	Zombie Survival Optimization (2012)	Nguyen and Bhanu (2012)	Foraging behavior of zombies	Swarm-based	1
202	Artificial Photosynthesis and Phototropism mechanism (2012)	Cai (2012)	Photosynthesis and phototropism in Plant growing process	Bio-Inspired	0
203	Camel algorithm (2016)	Ibrahim and Ali (2016)	The travelling behavior of camels	Swarm-based	0
204	Crystal Energy Optimization Algorithm (2016)	Feng et al. (2016)	General observations in lake freezing	Bio-inspired	–
205	Greedy Politics Optimization (2014)	Melvix (2014)	Political strategies adopted during state assembly elections	Population-based	–
206	Photosynthetic Learning Algorithm (1998)	Murase and Madano (1998)	The process of the reaction of carbon molecules in the dark reaction of photo-synthesis	Bio-inspired	–
207	Rain Water Algorithm (2017)	Biyanto (2017)	The pattern of physically rain water move-ments from air to the lowest place on the earth	Nature-inspired	–
208	Raccoon Optimization Algorithm (2018)	Koohi et al. (2018)	Hunting behaviors of raccoons for food	Bio-inspired	–
209	Tree physiology Optimization (2017)	Hanif (2017)	Plant growth system (root-shoot relation-ship)	Bio-inspired	–

our daily life such as, interior design, sports, music, vocational skills, military, politics, economics, interaction from our ecosystem.

Similarly, from Table 3, it is equally interesting to note that some of the classical algorithms such as simulated annealing with 45,020 impact, differential evolution with 20,661 impact, particle swarm optimization with 14,588 impact, genetic algorithm with 14,573 impact, and ant colony optimization with 11,527 impact, all have five significant digit numbers relative to their level of application relevance. However, the popularity achieved by these five standard algorithms can be attributed to the fact that each of these algorithm in one way or the other have concrete theoretical and mathematical analyses framework which supports their superior performances. Further, the theoretical and mathematical frameworks provide good reasons as to why these algorithms work well in real-world.

7 Metaheuristics applications areas

In this section, we present a summary of the different application areas for the 300 list of metaheuristic techniques presented in this paper (see the glossary of metaheuristics presented in Table 5). The advancement in computing powers in the last few decades has raised a large number of real-world optimization problems in different research and application domain that are extremely complex and difficult to solve. A metaheuristic technique is said to define algorithmic frameworks that can be applied to solve such complex problems in an approximate or near-optima way, by combining constructive methods with local and swarm-based search strategies, as well as strategies for escaping local optima that hinders the scalability of the exact methods as discussed in Torres-Jiménez and Pavón (2014).

In general, studies in the design and application of metaheuristics techniques has grown massively in the past three decades as a practical solution approaches to solving wide range of real-world optimization problems. More so, beside the fact that metaheuristics have scaled perfectly well in finding good quality solutions to many complex and NP-hard problems (Non-deterministic polynomial time-hard problems), they are also able to perform extremely very well in situations where the classical or traditional exact optimization methods would fail to deliver satisfactory results. Obviously, one of the main strength of metaheuristic techniques that has drawn wide interest to the scientific community and industry practitioners alike is the fact that metaheuristic problem solving techniques are able to generate good quality solution in relatively much less time than their exact optimization techniques counterparts. Therefore, because of these associated advantages, metaheuristics have find applications in a wide range of areas such as engineering design, management, factory or industries, finance, pattern recognition, networking, and scheduling. It is noteworthy to mention here that there is no universal metaheuristic approach to be applied to all the application domains. Therefore, after extensive analysis that was carried out, we have compiled the possible application areas for the respective identified metaheuristic techniques, which is presented in Table 4.

8 Glossary of metaheuristics

The following list presents a glossary of metaheuristic algorithms comprising of both classical and new generation algorithms. As aforementioned earlier, these two class of metaheuristic are differentiated based on the decades in which the algorithm was actually developed. Each algorithm in this list has been discussed previous and therefore, only their names a presented

Table 4 Application areas of the metaheuristic algorithms (application area citations are not included due to page limit)

S. no	Algorithm	Application areas
1	African Buffalo Optimization	Travelling salesman problem, collaborative team formation in a social network, PID controller parameter tuning, scheduling, channel allocation optimization
2	African Wild Dog Algorithm	Flowshop scheduling problem, engineering problems
3	Anarchic Society Optimization	Optimal PID control of Automatic Voltage Regulation (AVR) system, job-shop scheduling problem, flowshop scheduling problem
4	Animal Migration Optimization Algorithm	Clustering, multicast routing problem, engineering problems
5	Ant colony optimization	Scheduling, vehicle routing problems, travelling salesman problem, feature selection, image classification
6	Ant Lion optimization	Feature selection, neural network training, parameter optimization, optimal location and sizing of renewable distributed generations, flexible process planning problem, hydraulic turbine governing system parameter identification, multi area power system, parallel machine scheduling, antenna array synthesis
7	Artificial Algae Algorithm	Economic load dispatch problem, multi-objective engineering problems knapsack problem, binary optimization problems
8	Artificial bee colony algorithm	Scheduling, estimation of transportation energy demand, forecasting the blast-produced ground vibration, travelling salesman problem, engineering problem, clustering
9	Artificial Chemical Reaction Optimization Algorithm	Prediction of stock market indices, financial time series forecasting, knapsack problem, job scheduling, robotics
10	Artificial Cooperative Search	Numerical optimization problems, forecasting of electric energy consumption, economic dispatch problems, parameter identification of chaotic systems, optimal loading of multi-chiller system
11	Artificial Ecosystem Algorithm	Travelling salesman problem
12	Artificial Fish Swarm Algorithm	Neural network optimization, combinatory optimization problems, data clustering, wavelet threshold optimization, job scheduling, hydrothermal scheduling, spread spectrum code estimation
13	Artificial Immune System	Data analysis, multi-objective optimization problems, flow shop scheduling problem, computer security, structural health monitoring, tool breakage detection
14	Artificial Plant Optimization Algorithm	Bioinformatics, coverage optimization problem in wireless sensor network
15	Artificial Searching Swarm Algorithm	Constraint optimization problems, electromagnetic device optimization
16	Atmosphere Clouds Model	Optimal reactive power dispatch problem
17	Backtracking Search Optimization	Numerical optimization problems, multi-type distributed generators, optimal power flow problem, parameter identification of hyperchaotic systems, wind speed forcasting
18	Bacterial Evolutionary Algorithm	Data clustering, fuzzy system design

Table 4 (continued)

S. no	Algorithm	Application areas
19	Bacterial Foraging Algorithm	Global optimization problems, economic emission load dispatch, optimization in dynamic environments, solar photovoltaic parameter estimation, optimal multilevel thresholding, image segmentation, optimal power flow problem, etc
20	Bacterial Swarming	Modelling of transformer winding, optimal power flow problem
21	Bat Algorithm	Optimization, classifications, image processing, feature selection, scheduling, data mining
22	The Bees Algorithm	Function optimization, optimization in chemical engineering, neural networks training, the production scheduling problem, recognition of handwritten and many others
23	Big bang–big crunch	Structural damage detection, Linear Time Invariant Reduced Order System, structural design optimization, clustering, etc
24	Biogeography Based Optimization	Power systems, feature selection, scheduling, image enhancement and fusion, etc
25	Bird mating optimizer	Structural damage identification, voltage imbalance and deviation, scheduling
26	Bird swarm algorithm	Travel salesman problem, load dispatch and power generation problem
27	Black holes algorithm	Clustering, membrane computing, set covering problems, feature selection and classification
28	Blind, Naked Mole-rats Algorithm	Clustering
29	Brain Storm Optimization	Power dispatch problem, economic dispatch problem, grid scheduling, stock index forecasting
30	Bull Optimization Algorithm	Continuous optimization problems
31	Bumble Bees Mating Optimization	Global optimization problems, vehicle routing, Multicast Routing Problem, scheduling problem, Traveling Salesman Problem, power dispatch problem
32	Butterfly Optimization Algorithm	Engineering design problems
33	Butterfly Optimizer	Global optimization problems, phase load balancing
34	Camel herd Algorithm	Flexible job scheduling problems
35	Cat swarm optimization	Information hiding, aircraft schedule recovery, image processing tasks (segmentation, feature-extraction, classification and image generation), workflow scheduling in cloud computing environment, clustering
36	Central force optimization	Clustering, training neural network, water transmission pipeline, Pressure irrigation networks
37	Charged system search	Engineering design problems, time–cost optimization problem, Construction site layout planning optimization, power dispatch problem, Structural damage detection, water distribution networks

Table 4 (continued)

S. no	Algorithm	Application areas
38	Chicken swarm optimization	Multi-objective optimization problems, Engineering problems, economic dispatch problem, maximum power point tracking control of the photovoltaic system, travelling salesman problem
39	Clonal Selection Algorithm	Engineering problems, pattern recognition, machine learning, travelling salesman problem, microstrip coupler design
40	Cockroach Swarm Optimization	Travel planning, travel salesman problem
41	Colliding bodies optimization	Construction management, optimal design of truss structure, identification of Hammerstein plant, power flow problem
42	Community of scientist optimization	Distributed optimization
43	Consultant-Guided search	Travelling salesman problem, Quadratic Assignment Problem
44	The coral reefs optimization algorithm	Deployment of mobile network, design of off-shore wind farm, engineering problems, wind speed prediction
45	Covariance Matrix Adaptation–Evolution Strategy	Optimal control of hepatitis B infection, generation expansion planning problem, space flight trajectory optimization, analog circuit design
46	Crow search algorithm	Engineering optimization problems, feature selection, magnetic resonance image segmentation, diagnosis of Parkinson's disease, radial distribution networks, optimal third-order high-pass filter designs, evaluation of groundwater quality, electromagnetic optimization, economic and emission dispatch
47	Crystal Energy Optimization Algorithm	Large-scale distributed parallel optimization, traveling salesman problems
48	Cuckoo optimization algorithm	Multi-Input Multi-Output (MIMO) distillation column process, engineering optimization, engineering problems, extraction of uranium from water samples, single row facility layout problem, production planning problem
49	Cuckoo search	Parameter estimation, power dispatch problem, Planar Graph Coloring Problem, Inverse Geometry Heat Conduction Problems, neural network training, knapsack Problems, software effort estimation
50	Cultural algorithm	Image matching, data mining, knowledge integration, image detection, routing problem
51	Cuttlefish optimization	Feature selection, intrusion detection, diagnosis of Parkinson disease, parameter tuning, instance selection
52	Dialectic Search	Constraint satisfaction, continuous optimization, and combinatorial optimization
53	Differential evolution	Power system optimization, Optimal Power Flow, engineering problem, circle detection in computer vision, power plant control, economic load dispatch problem, quantitative interpretation of self-potential data in geophysics, crop planning

Table 4 (continued)

S. no	Algorithm	Application areas
54	Differential Search Algorithm	Parameter optimization, structure design problem, distribution system reliability optimization problem
55	Dolphin echolocation algorithm	Layout optimization, design of steel frame structures, manufacturing cell design problem, Truss optimization
56	Dragonfly algorithm	Submarine propeller design problem, wireless node localization, feature selection, economic dispatch problem, parameter optimization, tracking the Global Maximum Power Point (GMPP) of a photovoltaic (PV) system, image thresholding, optimization of tuning PID cascade control system
57	Duelist Algorithm	Optimization of Energy Efficiency and Conservation in Green Building, Economic Optimization of Petlyuk Distillation Column Design, Optimization of Steam Injection in Enhanced Oil Recovery
58	Eagle strategy	Design of frame strategy, power loss minimization, engineering problems
59	Earthworm Optimization Algorithm	Global optimization problems, smart grid management, power scheduling, Bound Constrained Optimization Problems
60	Eco-Inspired evolutionary algorithm	Numerical optimization, Protein Structure Prediction problem
61	Egyptian Vulture Optimization	Knapsack problem, travelling salesman problem, manufacturing cell design problem, vehicle routing problem, speech emotion recognition, road traffic management
62	Electro-magnetism Optimization	Circle detection in computer vision, power flow problem
63	Elephant Herding Optimization	Image thresholding, optimal placement of drones, Unmanned aerial vehicle path planning problem, parameter tuning of SVM, energy resource accommodation problem in distribution systems, PID controller tuning, load frequency control in power system, SVM optimization, Erythemato-Squamous Diseases Detection
64	Elephant Search Algorithm	NP-hard optimization and travelling salesman problem, clustering, microarray data analysis, distribution of Snack food
65	Elephant swarm water search algorithm	Gene regulatory network
66	Emperor Penguin Optimizer	Engineering design problems
67	Exchange Market Algorithm	Economic load dispatch problem, optimum active power dispatch problem
68	FIFA World Cup Algorithm	PID controller tuning
69	Firefly algorithm	Digital image compression, feature selection, classification, engineering design problems, scheduling problems, load dispatch problems, travelling salesman problem, clustering, neural network training, etc
70	Fireworks algorithm for optimization	GPU-based optimization, engineering problem, parameter optimization, portfolio optimization problem

Table 4 (continued)

S. no	Algorithm	Application areas
71	Fish-school Search	Data clustering, feature selection, Supply Chain Network Planning Problem
72	Fish swarm algorithm	Neural networks optimization, clustering, travelling salesman problem, signal denoising processing, job scheduling in grid computing
73	Flower Pollination Algorithm	Parameter optimization, economic dispatch problem, optimization of truss structures, multidimension function optimization problems, solving sudoku puzzles, identifying essential proteins, visual tracking, Unmanned Undersea Vehicle Path Planning Problem, Assembly sequence optimization
74	Flying elephant algorithm	Clustering, distance geometry, covering solid bodies with spheres, non-differentiable problems
75	Forest Optimization Algorithm	Data mining, feature selection
76	Fruit Fly Optimization Algorithm	Neural network optimization, parameter optimization, Knapsack problem, scheduling problem, NN optimization, PID controller tuning, parameter optimization
77	Galaxy-based Search Algorithm	Principal components analysis, image segmentation, object tracking, capacity enhancement, economic dispatch problem
78	Gases Brownian motion Optimization	Scheduling problem, economic load dispatch problem
79	Gene Expression Programming	Prediction of cervical cancer, real parameter optimization, classification, forecast problem, time series prediction, association rule mining
80	General Relativity Search Algorithm	Real number space, power systems
81	Genetic algorithm	Power system, image reconstruction, scheduling, engineering, routing, feature selection, filtering recommender system, travelling salesman problem, electromagnetic optimization
82	Glowworm swarm optimization	Wireless sensor network, robotics, clustering, economic dispatch problem, knapsack problem, image segmentation
83	Golden ball	Travelling salesman problem, vehicle routing problem, flow shop scheduling, satisfaction problem, bin packing problem
84	Good Lattice Swarm Algorithm	Engineering problem
85	Grasshopper Optimization Algorithm	Feature selection, truss design problem, Cantilever beam design problem, paremeter optimization, engineering design problems
86	Gravitational Search Algorithm	Optimal power flow problem, filter modeling, neural network training, parameter identification, economic and emission dispatch solution, reactive power dispatch problem

Table 4 (continued)

S. no	Algorithm	Application areas
87	Great Deluge Algorithm (and Record-to-record Travel)	Course timetabling, preventive maintenance optimization problem, channel assignment problem, reliability optimization of a complex system, optimal redundancy allocation
88	Great Salmon Run	Shape and Size Design of Truss Structures, structure prediction of aggregated artificial neural network
89	Greedy Politics Optimization	Multi-dimensional test functions
90	Grenade Explosion Algorithm	Engineering problems, optimal power flow problem, optimal phasor measurement unit placement, optimization of Plate-Fin Heat Exchanger
91	Grey Wolf Optimizer	Engineering problem, feature selection, power system, maximum power point tracking (MPPT) design for a photovoltaic (PV) system, economic load dispatch problems
92	Group Counseling Optimization	Multi-objective optimization problem
93	Group Search Optimizer	Economic dispatch problem, optimal location and capacity of distributed generations (DGs) in distribution networks, power dispatch problem, mechanical design optimization problems, truss structure, neural network training, coordination of directional overcurrent relays in power systems, optimal power flow problems, structural design
94	Harmony Search Algorithm	Travelling salesman problem, engineering problems, job scheduling problem, data mining, data mining, optimization of truss structure, optimization for distribution generation system, economic load dispatch problem, single area unit commitment problem
95	Heart Algorithm	Data clustering, numerical optimization
96	Heat Transfer Search algorithm	Truss structure optimization, predicting and optimizing the wire electrical discharge machining (WEDM) process parameters, economic dispatch problem, structural optimization
97	Hierarchical Swarm Model	Discrete and continuous optimization problem
98	Honey-bees mating optimization algorithm	Traveling salesman problem, clustering, optimal reservoir operation, financial classification problems, vehicle routing problem
99	Hoopoe Heuristic Optimization	Optimization of machine control parameters
100	Human-Inspired algorithms	Continuous function optimization
101	Hunting search algorithm	Extracting TSK-type neuro-fuzzy model, traveling salesman problem, optimization of steel cellular beams, quadratic optimization problem
102	Hydrological cycle algorithm	Continuous optimization problems, travelling salesman problem

Table 4 (continued)

S. no	Algorithm	Application areas
103	Imperialist Competitive Algorithm	Optimization of skeletal structures, clustering, integrated product mix-outsourcing optimization problem, image matching in feature tracking, load–frequency control of power systems, design of a linear induction motor, prediction oil flow rate of the reservoir, design an optimal antenna array, engineering problems, scheduling problem
104	Intelligent gravitational search algorithm	Design of optimal fuzzy system, robotics, engineering
105	Intelligent Water Drops Algorithm	Travelling salemen problem, multiple knapsack problem, scheduling problems, single unmanned combat aerial vehicle smooth trajectory planning problem, optimal data aggregation trees for the wireless sensor networks, vehicle routing problem, economic load dispatch problem, waste collection problem
106	Interior search algorithm	Engineering problems, optimal power flow problem
107	Invasive tumor growth optimization algorithm	SVM parameter optimization, detecting SNP-SNP interactions for complex diseases
108	Invasive Weed Optimization	Engineering problems, recommender system, Design of Non-Uniform Circular Antenna Arrays, electromagnetic problems, optimization of antenna problems, traveling salesman problem, time-modulated linear antenna array synthesis, unit commitment problem, scheduling problem, non-linear problems and clustering
109	Ions Motion Algorithm	Continuous absolute p-Center location problem
110	Japanese Tree Frogs Calling algorithm	Distributed graph coloring
111	Kaizen Programming	Improved prediction of material properties of concrete, feature construction, lawn mower problem
112	Keshtel Algorithm	Transportation problem
113	Killer Whale Algorithm	Optimization of energy efficiency
114	Krill Herd algorithm	Economic load dispatch problem, global optimization problem
115	League championship algorithm	Engineering problems, optimal power flow problem, scheduling problems, optimal resource allocation
116	Lightning Search Algorithm	Optimization of PV inverter controller, neural network optimization, Parameter Extraction of Solar Cell Models, determining the optimal value of the weighting factor in wind power model
117	Lion Optimization Algorithm	Efficient Load Balancing in Cloud Computing
118	Locust Swarms	Global optimization problems, joint replenishment problem
119	Locust search	Image segmentation
120	Magnetotactic Bacteria Optimization Algorithm	Multimodal optimization, power spectrum optimization, SVM parameter optimization

Table 4 (continued)

S. no	Algorithm	Application areas
121	Memetic Algorithm	Travelling salesman problem, exam timetabling, flow shop scheduling problem, instance conference problem, supply chain network design, air transportation system, protein–protein interaction (PPI) network alignment, automatic data clustering, calibration of traffic flow model, etc
122	Migrating Birds Optimization	Quadratic assignment problem, knapsack problems, task allocation problems, scheduling problems, Machine-Part Cell Formation Problems
123	Mine Blast Algorithm	Economic dispatch problem, optimal sizing of hybrid photovoltaic wind fuel cell system, water distribution system, optimal allocations and sizing of capacitors in various distribution systems, PI controllers parameter optimization, photovoltaic generating systems, optimizing truss structure, parameter optimization of PID controllers, etc
124	Monarch Butterfly Optimization Algorithm	Knapsack problem, neural network training, vehicle routing problem, RFID network planning problem, clustering optimization, etc
125	Monkey search algorithm	Flow shop scheduling problem, knapsack problem, capacitor allocation in distributed system, health monitoring sensor placement optimization, task scheduling in cloud computing
126	Moth-flame Optimization Algorithm	Optimal machining parameters in manufacturing process, image segmentation, parameter extraction, PID controller, Optimal Nonlinear Feedback Control Design, feature selection, optimal power flow problem, tomato disease detection
127	Multi-bjective Optimization Algorithms Based on sperm Fertilization Procedure	Wireless sensor networks optimization problems
128	Multi-verse Optimizer	Neural network training, data clustering, feature selection, knapsack problems, parameter extraction of photovoltaic generating units
129	Optics Inspired Optimization	Engineering problems, mechanical design optimization problem, optimum design of steel tower structures, PID parameter tuning, routing in wireless sensor network, cluster head selection
130	Parliamentary Optimization Algorithm	Web page classification
131	Particle swarm optimization	Feature selection, job scheduling, financial time series forecast, vapor–liquid equilibrium problems, engineering, economic dispatch problem, PID controller tuning, scheduling problem, medical diagnosis, etc
132	Penguins Search Optimization Algorithm	Travelling salesman problem, association rule mining, optimal operation of reservoir systems
133	Photosynthetic Learning Algorithm	Traveling salesman problem
134	Pity Beetle Algorithm	Engineering problem

Table 4 (continued)

S. no	Algorithm	Application areas
135	Plant Propagation Algorithm	Process design problem, engineering problem
136	POPMUSIC: Partial Optimization Metaheuristic Under Special Intensification Conditions	Clustering, Identification of amino acid residues, predicting protein mutant stability changes, point feature label placement problem, routing problem, berth allocation problem, etc
137	Queen-bee Evolution	Economic dispatch problem, control system
138	Rainfall optimization algorithm	Engineering problem
139	Raven Roosting Optimization Algorithm	Scheduling problem
140	Ray Optimization	Mechanical problems, optimization of truss structure
141	Reincarnation algorithm	Discrete optimization problems
142	River Formation Dynamics	Traveling salesman problem, NP-hard problems, NP-complete problems
143	Ring Seal Search	Optimization problems
144	Roach Infestation Optimization	Extraction of textual features, neural network learning, engineering problem
145	Rooted Tree Optimization Algorithm	Economic dispatch problems, power control of wind turbine, protein folding prediction
146	Runner-root Algorithm	Network reconfiguration problem, feature selection
147	Salp Swarm Algorithm	Engineering problems, feature selection, parameter extraction, image segmentation, predicting chemical compound activities. PID controller
148	Saplings Growing Up Algorithm	Scheduling problem, supply chain management, stacking sequence optimisation of laminate composites, joint economic lot sizing problem, vehicle routing problem
149	The scientific algorithms	Traveling salesman problem
150	Shark Smell Optimization	Wind power prediction, optimal placement of capacitors, multiyear expansion planning of distribution networks, optimal distribution of power
151	Sheep Flocks Heredity Model	Scheduling problems, loop layout problem, transportation problem
152	Shuffled complex evolution	Optimal design of water distribution, phase stability problem, infrastructure works programming problem, parameter optimization
153	Shuffled Frog Leaping Algorithm	Optimization of water distribution, clustering, unit commitment problem, mixed model assembly line sequencing problem, project management, scheduling problem, optimal tuning of PID controllers, traveling salesman problem

Table 4 (continued)

S. no	Algorithm	Application areas
154	Simulated annealing	Feature selection, heat exchanger network synthesis, vehicle routing problem, traveling salesman problem, pressure-swing distillation, broadband diffusion metasurface, image encryption, electric load forecasting, inventory routing problem
155	Sine Cosine Algorithm	Feature selection, wind speed forecasting, engineering problems, optimal power flow problem, optimization of a vehicle engine connecting rod, parameter optimization, visual tracking, image binarization
156	Small-world Optimization Algorithm	Sequencing problem, feature selection
157	Social Cognitive Optimization	Reactive power optimization problem, nonlinear equation problem, clustering, engineering problem
158	Social emotional optimization	Directing orbits of chaotic systems, parameter optimization, optimal coverage problem, traffic flow forecasting
159	Social Spider Algorithm	Economic load dispatch problem, neural network training, biochar yield prediction, electromagnectic optimization, clustering, base station switching problem
160	Sperm Motility Algorithm	Fractional programming problems under uncertainty
161	Sperm Whale Algorithm	Production optimization problems, parameter optimization
162	Sperm Swarm Optimization Algorithm	Wireless sensor network
163	Spider Monkey Optimization	Electromagnetics, optimal placement and sizing of capacitor, plant leaf disease identification, thinning of concentric circular antenna arrays
164	Spiral dynamics inspired optimization	Mixed integer nonlinear programming problems, engineering, optimizing PID controller parameters
165	Stochastic Diffusion Search	Training of neural network, Short-term load forecast of electrical power system
166	Stochastic fractal search	Power systems, optimization of the surface grinding process, parameter identification, PID controller parameter tuning, SVM parameter optimization
167	Strawberry plant algorithm	Engineering problems
168	Swallow Swarm Optimization Algorithm	Traveling salesman problem
169	Symbiotic Organisms Search	Engineering problems, structural design optimization, optimal power flow problem, truss design problem, project scheduling problem, task scheduling in cloud computing, economic dispatch problem, time–cost–labor utilization tradeoff problem, congestion management, etc
170	Tabu Search algorithm	Flow-shop problem, network synthesis, vehicle routing problem, job scheduling problem, Millimeter-Wave Massive MIMO Systems, medicine, traveling salesman problem

Table 4 (continued)

S. no	Algorithm	Application areas
171	Teaching–learning based Optimization	Mechanical design problems, unconstrained optimization problems, planar steel frames design, parameter optimization, optimization of two stage thermoelectric cooler
172	Termite Colony Optimization	Wireless sensor network
173	Tree Seed Algorithm	Pressure vessel design problem, neural network training, ultrasound images, optimal powerflow problem, large-scale binary optimization
174	Variable Neighborhood Descent Algorithm	Job scheduling problem, arc routing problem, vehicle routing problem, waste collection problem, traveling salesman problem, redundancy allocation problem
175	Viral systems	Transportation problem, wind turbine placement problems, knapsack problem
176	Virus Colony Search	Engineering problems, optimal placement of distributed generators
177	Virus Optimization Algorithm	Scheduling problems
178	Vortex Search Algorithm	Analog active filter component selection problem, single mixed refrigerant natural gas liquefaction process
179	Wasp Swarm Optimization	Clustering, feature selection, dynamic MAX-SAT problems
180	Water Cycle Algorithm	Engineering problems, optimal operation of reservoir systems, multi-objective problems, power dispatch problem, chaos suppression problem, weight optimization of truss structure, power flow problem, etc
181	Water Evaporation Optimization	Engineering problems, truss design problems, economic dispatch problem
182	Water Wave Optimization	Scheduling problem, traveling salesman problem, vehicle routing problem, image match
183	Water-flow Algorithm	Scheduling problem, manufacturing cell formation problems, object grouping problems, traveling salesman problem
184	Whale Optimization Algorithm	Neural network training, parameter identification, scheduling problem, sizing optimization of skeletal structures, electrical distribution network
185	Wind Driven Optimization	Electromagnetics, multilevel thresholding problem, scheduling problem, robotics, power systems, etc
186	Wolf Search Algorithm	High dimensional complex optimization problems, feature selection
187	Zombie Survival Optimization	Image search
188	Artificial infectious disease optimization	-
189	Asexual Reproduction Optimization	Training a feed-forward networks, structure learning approach for Bayesian networks, Bidirectional inductive power transfer system
190	Bean Optimization Algorithm	Travelling Salesman Problem, Reactive Power Problem

Table 4 (continued)

S. no	Algorithm	Application areas
191	Dendritic Cells Algorithm	SYN scan detection, online break-in fraud detection
192	Ecogeography-Based Optimization	University course timetabling, evolutionary deep neural network for predicting morbidity of gastrointestinal infections by food contamination
193	Evolution strategies	Scalable alternative to reinforcement learning
194	Marriage in Honey Bees Optimization	Stochastic dynamic programming, Forecasting output of integrated circuit industry, Materialized view selection
195	SuperBug Algorithm	–
196	Stem Cells Algorithm	Data clustering, bottom hole circulating pressure in underbalanced drilling
197	Swine Influenza Models Based Optimization	optimal allocation of DG in radial distribution network, ECG filtering
198	Self-Organizing Migrating Algorithm	Reliability-redundancy optimization of systems, Electromagnetic optimization, solving large scale global optimization problems
199	Variable Mesh Optimization	Multimodal Optimization, solve continuous optimization problems
200	Andean Condor Algorithm	Solve problems of Continuous Domains
201	Artificial Tribe Algorithm	solving constrained optimization problems
202	Bald Eagle Search	–
203	Bison Behavior Algorithm	–
204	Collective Animal Behavior	Multimodal function optimization, optimal allotment of distributed generation sets and shunt capacitors in radial distribution system
205	Cheetah Based Algorithm	–
206	Cricket Algorithm	Training artificial neural network
207	Coyote optimization algorithm	parameters extraction of three-diode photovoltaic models of photovoltaic modules, Economic Dispatch Integrated Wind Power
208	Flocking based algorithm	Data clustering, maintain connectivity in mobile wireless ad hoc networks
209	Group Escape Behavior	–
210	Harris Hawks Optimization	Structural design optimization of vehicle components, Satellite image de-noising
211	Honey Bee Social Foraging Algorithms	Resource allocation, feedback control of smart lights

Table 4 (continued)

S. no	Algorithm	Application areas
212	Natural Aggregation Algorithm	Hypercube
213	Laying chicken algorithm	–
214	Lion's Algorithm	Standard and large scale bilinear system identification, feature selection method for support vector machines
215	Mouth Brooding Fish algorithm	Cost optimization of reinforced concrete one-way ribbed slabs, seismic fragility analysis
216	Mosquito Flying Optimization	Artificial neural network model for the alarm tuning of process fault detection systems, Load Frequency Control of Microgrid Considering Renewable Source Uncertainties
217	Meerkats-inspired Algorithm	–
218	MOX Optimization Algorithm	Static transmission network expansion planning, evolutionary algorithm in transmission network expansion planning
219	Naked Mole-Rat Algorithm	–
220	Nomadic People Optimizer	–
221	Optimal Foraging Algorithm	Drilling path optimization
222	Pigeon-Inspired Optimization	Many-objective optimization problems, Three-dimensional path planning for uninhabited combat aerial vehicle
223	Population Migration Algorithm	Hybrid multi-objective, training RBF neural networks
224	Prey-Predator Algorithm	Adaptive step length, group hunting scenario
225	Red Deer Algorithm	–
226	Rhino Herd Behavior	–
227	Satin Bowerbird Optimizer	Software development effort estimation, A complex-valued encoding
228	Spotted Hyena Optimizer	Feature selection, Predicting the Shear Strength of Soil
229	Swarm-Inspired Projection Algorithm	Exploring and weighting features for financially distressed construction companies
230	Slime Mold Algorithm	–
231	Seeker Optimization Algorithm	Optimal reactive power dispatch, constrained optimization problems
232	Squirrel Search Algorithm	Multi-region combined heat and power economic dispatch incorporating renewable energy sources, Maximum Likelihood DOA Estimation and Application for MEMS Vector Hydrophone Array
233	See-See Partridge Chicks Optimization	Clustering problem

Table 4 (continued)

S. no	Algorithm	Application areas
234	Termite-hill Algorithm	Mobile sink for improving network lifetime in wireless sensor networks
235	Wolf Colony Algorithm	Precision time synchronization control method for smart grid, leader strategy
236	Artificial Electric Field Algorithm	–
237	Artificial Physics Optimization Algorithm	Security-constrained optimal power flow with wind and thermal power generators, Vulnerability assessment and reconfiguration of microgrid
238	Light Ray Optimization	–
239	Magnetic Optimization Algorithm	Training multi-layer perceptron, Data clustering
240	Method of Musical Composition	–
241	Particle Collision Algorithm	Nuclear reactor core design optimization, Optimization of feedforward neural network
242	Radial Movement Optimization	Estimating the parameters of fuel cost function in thermal power plants, calculating the upper bound of ultimate bearing capacity of shallow foundation on unsaturated soil
243	Space Gravitational Optimization	Single MR modality for automatic brain lesion detection and segmentation
244	Sonar Inspired Optimization	Engineering applications
245	States Matter Optimization Algorithm	–
246	Spiral Optimization Algorithm	–
247	Vibrating Particles System	Damage identification of truss structures
248	Artificial Chemical Process	Particulate processes and discrete dynamic systems
249	Integrated Radiation Optimization	–
250	Kinetic Gas Molecule Optimization	Nonconvex economic dispatch problem, Optimization of Shell and Tube Heat Exchanger Design in Organic Rankine Cycle System
251	Synergistic Fibroblast Optimization	Medical Image Denoising
252	Thermal Exchange Optimization	Structural damage identification
253	Bus Transportation Algorithm	–
254	Collective Decision Optimization Algorithm	Economic emission dispatch problem
255	Cognitive Behavior Optimization Algorithm	UAV with TLP model
256	Group Leaders Optimization Algorithm	Grid computing

Table 4 (continued)

S. no	Algorithm	Application areas
257	Human Evolutionary Model	–
258	Ideology Algorithm	–
259	Oriented Search Algorithm	Reactive Power Optimization
260	Queuing Search Algorithm	–
261	Tug of War Optimization	Optimum design of laterally-supported castellated beams
262	Unconscious Search	Training the feedforward neural network
263	Volleyball Premier League Algorithm	Global optimization problem, Interconnected Power System
264	Wisdom of Artificial Crowds Algorithm	Applied to light up, solve solitaire battleship puzzles
265	Tree Growth Algorithm	–
266	Yin-Yang Pair Optimization	Perturbation observer based fractional-order PID control of photovoltaics inverters for solar energy harvesting
267	Passing vehicle search	Topology optimization of truss subjected to static and dynamic constraints

Table 5 Glossary of the metaheuristic techniques

Algorithm	Acronym	Author	Year	Class
A				
African Buffalo Optimization	ABO	Odili et al	2015	Swarm-based
African Wild Dog Algorithm	AWDA	Subramanian et al	2013	Swarm-based
Anarchic Society Optimization	ASO	Ahmadi-Javid	2011	Swarm-based
Andean Condor Algorithm	ACA	Almonacid and Soto	2019	Population-based
Animal Migration Optimization Algorithm	AMO	Li et al	2014	Swarm-based
Ant Colony Optimization	ACO	Dorigo and Birattari	1991	Swarm-based
Ant Lion optimization	ALO	Mirjalili et al.	2015	Swarm-based
Artificial Algae Algorithm	AAA	Uymaz et al	2013	Bio-Inspired
Artificial Bee Colony algorithm	ABC	Karaboga and Basturk	2007	Swarm-based
Artificial Chemical Process	LARES	Irizarry	2004	Nature-inspired
Artificial Chemical Reaction Optimization Algorithm	ACROA	Alatas	2011	Nature-inspired
Artificial Cooperative Search	ACS	Civicioglu et al	2013	Nature-inspired
Artificial Ecosystem Algorithm	AEA	Adham and Bentley	2014	Nature-inspired
Artificial Electric Field Algorithm	AEFA	Yadav	2019	Population-based
Artificial Fish Swarm Algorithm	AFSA	Li	2002	Swarm-based
Artificial Flora Optimization Algorithm	AF	Cheng et al	2018	Bio-Inspired
Artificial infectious disease optimization	AIDO	Huang	2016	Bio-Inspired
Artificial Immune System	AIS	Dasgupta and Gonzalez	2003	Bio-inspired
Artificial Physics Optimization Algorithm	APO	Xie et al	2009	Population-based
Artificial Plant Optimization Algorithm	APOA	Li et al	2012	Bio-Inspired
Artificial Searching Swarm Algorithm	ASSA	Chen	2009	Swarm-based
Artificial Tribe Algorithm	ATA	Chen et al	2012	Bio-inspired
Artificial Photosynthesis and Phototropism Mechanism	APPM	Xingjuan	2012	Bio-Inspired
Artificial Swarm Intelligence	ASI	Rosenberg	2016	Swarm-based
Asexual Reproduction Optimization	ARO	Farasat et al	2010	Bio-Inspired
Atmosphere Clouds Model	ACM	Yan and Hao	2013	Evolutionary-based

Table 5 (continued)

Algorithm	Acronym	Author	Year	Class
B				
Backtracking Search Optimization	BSOA	Civicioglu	2013	Evolutionary-based
Bacteria Chemotaxis Algorithm	BC	Muller et al	2002	Swarm-based
Bacterial Colony Optimization	BSA	Niu and Wang	2012	Swarm-based
Bacterial Evolutionary Algorithm	BEA	Numaoka	1996	Evolutionary-based
Bacterial Foraging Algorithm	BFA	Passino	2002	Bio-inspired
Bacterial Swarming Algorithm	BSA	Tang et al	2007	Bio-inspired
Bald Eagle Search	BES	Alsattar et al	2019	Nature-inspired
Bat Algorithm	BA	Yang	2010	Swarm-based
Bean Optimization Algorithm	BOA	Zhang et al	2010	Bio-Inspired
The Bees Algorithm	BA	Pham et al	2005	Swarm-based
Big Bang–Big Crunch	BB-BC	Erol and Eksin	2006	Nature-based
Biogeography Based Optimization	BBO	Dan	2008	Nature-inspired
Bison Behavior Algorithm	BBA	Kazikov et al	2017	Swarm-based
Bird Mating Optimizer	BMO	Askarzadeh	2014	Evolutionary-based
Bird Swarm Algorithm	BSA	Meng et al	2016	Swarm-based
Black Holes Algorithm	BHA	Hatamlou	2013	Nature-inspired based
Blind, Naked Mole-Rats Algorithm	BNMR	Taherdangko et al	2013	Swarm-based
Brain Storm Optimization	BSO	Shi	2015	Bio-inspired
Bull Optimization Algorithm	BOA	Findik	2015	Evolutionary-based
Bumble Bees Mating Optimization	BBMO	Comellas and Martinez-Navarro	2009	Swarm-based
Bus Transportation Algorithm	BTA	Bodaghi and Samieefar	2019	Nature-inspired
Butterfly Optimization Algorithm	BOA	Arora and Singh	2019	Swarm-based
Butterfly Optimizer	BO	Kumar	2015	Swarm-based

Table 5 (continued)

Algorithm	Acronym	Author	Year	Class
C				
Camel Algorithm	CA	Ibrahim and Ali	2016	Swarm-based
Camel Herd Algorithm	CHA	Al-Obaidi	2017	Swarm-based
Cat Swarm Optimization	CSO	Chu	2006	Swarm-based
Central Force Optimization	CFO	Formato	2007	Nature-inspired
Charged System Search	CSS	Kaveh and Talatahari	2010	Nature-inspired
Cheetah Based Algorithm	CBA	Klein et al	2018	Swarm-based
Chicken Swarm Optimization	CSO	Meng	2014	Swarm-based
Clonal Selection Algorithm	CSA	De Castro and Von Zuben	2000	Bio-inspired
Cockroach Swarm Optimization	CSO	ZhaoHui and HaiYan	2010	Swarm-based
Cognitive Behavior Optimization Algorithm	CBOA	Li et al	2016	Nature-inspired
Collective Animal Behavior	CAB	Cuevas et al	2012	Swarm-based
Collective Decision Optimization Algorithm	CDOA	Zhang et al	2017	Nature-inspired
Colliding Bodies Optimization	CBO	Kaveh and Mahdavi	2014	Population-based
Community of Scientist Optimization	CoSO	Milani and Santucci	2012	Population-based
Consultant-Guided Search	CGS	Iordache	2010	Swarm-based
Coral Reefs Optimization Algorithm	CRO	Salcedo-Sanz et al	2014	Bio-inspired
Covariance Matrix Adaptation–Evolution Strategy	CMAES	Hansen et al	2003	Evolutionary-based
Coyote optimization algorithm	COA	Pierezan and Coelho	2018	Population-based
Cricket Algorithm	CA	Canayaz and Karci	2016	Nature-inspired
Crow Search Algorithm	CSA	Askarzadeh	2016	Swarm-based
Crystal Energy Optimization Algorithm	CEO	Feng	2016	Bio-inspired
Cuckoo Optimization Algorithm	COA	Rajabioun	2011	Swarm-based
Cuckoo Search	CS	Yang	2009	Swarm-based
Cultural Algorithms	CAs	Reynolds	1994	Evolution-based

Table 5 (continued)

Algorithm	Acronym	Author	Year	Class
Cuttlefish Algorithm	CFA	Eesa et al	2013	Bio-inspired
D				
Dendritic Cells Algorithm	DCA	Greensmith et al	2005	Bio-inspired
Dialectic Search	DS	Kadioglu and Sellmann	2009	Bio-inspired
Differential Evolution	DE	Storn and Price	1997	Population-based
Differential Search Algorithm	DSA	Civicioglu	2012	Evolutionary-based
Dolphin Echolocation	DE	Ray	2013	Swarm-based
A Dolphin Partner Optimization	DPO	Shiqin	2009	Bio-inspired
Dragonfly Algorithm	DA	Mirjalili	2016	Swarm-based
Duelist Algorithm	DA	Biyanto et al	2016	Population-based
E				
Eagle Strategy	ES	Yang and Deb	2010	Swarm-based
Earthworm Optimization Algorithm	EWA	Wang et al	2015	Swarm-based
Ecogeography-Based Optimization	EBO	Zheng et al	2014	Bio-inspired
Eco-Inspired Evolutionary algorithm	ECO	Parpinelli and Lopes	2011	Evolutionary-based
Egyptian Vulture Optimization	EVOA	Sur et al	2013	Swarm-based
Electro-magnetism Optimization	EMO	Cuevas et al		Nature-inspired
Elephant Herding Optimization	EHO	Wang et al	2015	Swarm-based
Elephant Search Algorithm	ESA	Deb et al	2015	Swarm-based
Elephant Swarm Water Search Algorithm	ESWSA	Mandal	2018	Swarm-based
Emperor Penguin Optimizer	EPO	Dhiman and Kumar	2018	Swarm-based
Emperor Penguins Colony	EPC	Harifi et al	2019	swarm-based
Evolution strategies	ES	Bayer and Schwefel	2002	Evolutionary-based
Exchange Market Algorithm	EMA	Ghorbani and Babaei	2014	Population-based

Table 5 (continued)

Algorithm	Acronym	Author	Year	Class
F				
FIFA World Cup Algorithm	WCA	Razmjooy et al	2016	Population-based
Firefly Algorithm	FA	Yang	2009	Swarm-based
Fireworks Algorithm	FA	Tan and Zhu	2010	Swarm-based
Fish-School Search	FSS	Bastos Filho	2008	Swarm-based
Artificial Fish Swarm Algorithm	AFSA	Li	2002	Swarm-based
Flocking based algorithm	FBA	Cui et al	2006	Swarm-based
Flower Pollination Algorithm	FPA	Yang	2012	Bio-inspired
Flying Elephant Algorithm	FEA	Xavier and Xavier	2016	Bio-inspired
Forest Optimization Algorithm	FOA	Ghaemi and Feizi-Derakhshi	2014	Evolutionary-based
Fruit Fly Optimization Algorithm	FFO	Pan	2012	Swarm-based
G				
Galaxy-based Search Algorithm	GbSA	Shah-Hosseini	2011	Nature-inspired
Gases Brownian Motion Optimization	GBMO	Abdechiri et al	2013	Evolutionary-based
Gene Expression Programming	GEP	Ferreira	2001	Nature-
General Relativity Search Algorithm	GRSA	Beiranvand and Rokrok	2015	Evolutionary-based
Genetic Algorithm	GA	Holland and Reitman	1978	Evolutionary-based
Glowworm Swarm Optimization	GSO	Krishnanand and Ghose	2009	Swarm-based
Golden Ball Algorithm	GBA	Osaba et al	2014	Population-based
Good Lattice Swarm Algorithm	GLSA	Su et al	2007	Swarm-based
Grasshopper Optimization Algorithm	GOA	Saremi et al	2017	swarm-based
Gravitational Search Algorithm	GSA	Rashedi et al	2009	Nature-inspired
Great Deluge Algorithm	GDA	Dueck	1993	Population-based
Great Salmon Run	GSR	Mozaffari et al	2012	Bio-inspired
Greedy Politics Optimization	GPO	Melvix	2014	Population-based

Table 5 (continued)

Algorithm	Acronym	Author	Year	Class
Grenade Explosion Method	GEM	Ahrari and Atai	2010	Nature-Inspired
Grey Wolves Optimizer	GWO	Mirjalili	2014	Bio-Inspired
Group Counseling Optimization	GCO	Eita and Fahmy	2009	Population-based
Group Escape Behavior	GEB	Min and Wang	2011	Nature-inspired
Group Leaders Optimization Algorithm	GLOA	Daskin and Kais	2011	Population-inspired
Group Search Optimizer	GSO	He et al	2006	Swarm-based
H				
Harmony Search Algorithm	HS	Geem et al	2001	Nature-inspired
Harris Hawks Optimization	HHO	Heidari et al	2019	Population-based
Heart Algorithm	HA	Hatamlou	2014	Bio-inspired
Heat Transfer Search algorithm	HTS	Patel and Savsani	2015	Nature-inspired
Hierarchical Swarm Model	HSO	Chen et al	2010	Swarm-based
Honey-bees Mating Optimization Algorithm	HBMO	Haddad et al	2006	Swarm-based
Honey Bee Social Foraging Algorithms	HSF	Quijano and Passino	2007	Bio-inspired
Hoopoe Heuristic Optimization	HH	El-Dosuky et al	2012	Swarm-based
Human Evolutionary Model	HEM	Montiel et al	2007	Nature-inspired
Human-Inspired Algorithms	HIA	Zhang et al	2009	Population-based
Hunting Search Algorithm	HuSA	Oftadeh and Mahjoob	2009	Population-based
Hydrological Cycle Algorithm	HCA	Wedyan et al	2017	Nature-based
I				
Ideology Algorithm	IA	Huan et al	2017	Nature-inspired
Imperialist Competitive Algorithm	ICA	Atashpaz-Gargari et al	2007	Evolutionary-based
Integrated Radiation Optimization	IRO	Chuang and Jiang	2007	Nature-inspired
Intelligent Gravitational Search Algorithm	IGSA	Askari and Zahiri	2012	Nature-inspired
Intelligent Water Drops Algorithm	IWD	Hamed Shah	2007	Population-based

Table 5 (continued)

Algorithm	Acronym	Author	Year	Class
Interior Search Algorithm	ISA	Gandomi	2014	Nature-inspired
Invasive Tumor Growth Optimization Algorithm	ITGO	Tang et al	2015	Bio-inspired
Invasive Weed Optimization	IWO	Mehrabian and Lucas	2006	Swarm-based
Ions Motion Algorithm		Javidy et al	2015	Nature-inspired
J				
Jaguar Algorithm	JA	Chen et al	2015	Swarm-based
Japanese Tree Frogs Calling Algorithm	FrogMIS	Hernández and Blum	2012	Swarm-based
K				
Kaizen Programming	KP	De Melo	2014	Evolutionary-based
Keshtel Algorithm	KA	Hajiaghaei-Keshteli and Aminnayeri	2014	Swarm-based
Killer Whale Algorithm	KWA	Biyanto et al	2017	Swarm-based
Kinetic Gas Molecule Optimization	KGMO	Moein and Logeswaran	2014	Swarm-based
Krill Herd Algorithm	KH	Gandomi and Alavi	2012	Swarm-based
L				
Laying chicken algorithm	LCA	Hosseini	2017	Bio-inspired
League Championship Algorithm	LCA	Kashan	2009	Population-based
Lightning Search Algorithm	LSA	Shareef et al	2015	Evolutionary-based
Light Ray Optimization	LRO	Shen and Li	2009	Nature-inspired
Lion's Algorithm	LA	Rajakumar	2014	Nature-inspired
Lion Optimization Algorithm	LOA	Yazdani and Jolai	2016	Population-based
Locust Search	LS	Cuevas	2015	Swarm-based
Locust Swarm	LS	Chen	2015	Swarm-based
M				
Magnetotactic bacteria optimization algorithm	MBOA	Mo and Xu	2013	Swarm-based
Magnetic Optimization Algorithm	MOA	Tayarani-N and Akbarzadeh-T	2008	Nature-inspired

Table 5 (continued)

Algorithm	Acronym	Author	Year	Class
Marriage in honey bees optimization	MBO	Abbas	2001	Swarm-based
Memetic Algorithm	MA	Radcliffe and Surry	1994	Evolutionary-based
Method of Musical Composition	MMC	Mora-Gutiérrez et al	2014	Nature-inspired
Meerkats-inspired Algorithm	MiA	Klein and dos Santos Coelho	2018	Population-inspired
Migrating Bird Optimization	MBO	Duman et al	2012	Swarm-based
Mine Blast Algorithm		Sadollah et al	2012	Nature-inspired
Monarch Butterfly Optimization	MBO	Wang et al	2015	Swarm-based
Monkey Search Algorithm		Mucherino and Onur	2007	Population-based
Moth-Flame Optimization Algorithm	MFO	Mirjalili	2015	Swarm-based
Multi-Objective Optimization Algorithms Based on sperm Fertilization Procedure	MOSFP	Hisham et al	2018	Bio-inspired
Multi-verse Optimizer	MVO	Mirjalili et al	2017	Nature-inspired
Mosquito Flying Optimization	MFO	Alauddin	2016	Nature-inspired
Mouth Brooding Fish algorithm	MBFA	Jahani and Chizari,	2018	Nature-inspired
MOX Optimization Algorithm	MOX	Arif	2011	Bio-inspired
N				
Natural Aggregation Algorithm	NAA	Luo et al	2016	Population-based
Naked Mole-Rat Algorithm	MNR	Salgotra and Singh	2019	Nature-inspired
Nomadic People Optimizer	NPO	Salih and Alsewari	2019	Population-based
O				
Optics Inspired Optimization	OIO	Kashan	2015	Nature-inspired
Optimal Foraging Algorithm	OFA	Zhu and Zhang	2017	Population-based
Oriented Search Algorithm	OSA	Zhang et al	2008	Nature-inspired
P				
Paddy Field Algorithm	PFA	Premaratne et al	2009	Bio-inspired

Table 5 (continued)

Algorithm	Acronym	Author	Year	Class
Parliamentary Optimization Algorithm	POA	Borji	2007	Evolutionary-based
Particle Collision Algorithm	PCA	Sacco and De Oliveira	2005	Swarm-based
Particle Swarm Optimization	PSO	Eberhart and Kennedy	1995	Swarm-based
Passing vehicle search	PVS	Savsani and Savsani	2016	Population-based
Penguins Search Optimization Algorithm	PeSOA	Gheraibia and Moussaoui	2013	Swarm-based
Photosynthetic Learning Algorithm	PLA	Murase and Madano	1998	Bio-inspired
Pity Beetle Algorithm	PBA	Kallioras et al	2018	Swarm-based
Pigeon-Inspired Optimization	PIO	Duan and Qiao	2014	Swarm-based
Plant Growth Optimization	PGO	Cai et al	2008	Bio-based
Plant Propagation Algorithm	PPA	Salhi and Fraga	2011	Bio-based
Partial Optimization Metaheuristic Under Special Intensification Condition Algorithm	POPMUSIC	Taillard and Voss	2002	–
Prey-Predator Algorithm	PPA	Tilahun and Ong,	2015	Nature-inspired
Political Optimizer	PO	Askari et al	2020	Population-based
Population Migration Algorithm	PMA	Zong_yuan	2003	Population-based
Q				
Quantum-Inspired Bacterial Swarming Optimization	QBSO	Cao and Gao	2012	Swarm-based
Queen-Bee Evolution	QBE	Jung	2003	Evolutionary-based
Queuing Search Algorithm	QS	Zhang et al	2018	Nature-inspired
R				
Rain Water Algorithm	RWA	Biyanto	2017	Nature-inspired
Raccoon Optimization Algorithm	ROA	Koohi et al	2019	Bio-inspired
Radial Movement Optimization	RMO	Rahmani and Yusof	2014	Swarm-based
Rainfall Optimization Algorithm	RFO	Aghay Kaboli et al	2017	Nature-inspired
Raven Roosting Optimization Algorithm	RRO	Brabazon et al	2016	Swarm-based

Table 5 (continued)

Algorithm	Acronym	Author	Year	Class
Ray Optimization	RO	Kaveh and Khayatazad	2012	Nature-inspired
Red Deer Algorithm	RDA	Fard, and Hajiaghaei-Keshteli	2016	Nature-inspired
Reincarnation Algorithm	RA	Sharma	2010	Evolutionary-based
Rhino Herd Behavior	RHB	Wang et al	2018	Nature-inspired
River Formation Dynamics	RFD	Rabanal et al	2007	Nature-inspired
Ringed Seal Search	RSS	Saadi et al	2016	Bio-inspired
Roach Infestation Optimization	RIO	Havens et al	2008	Swarm-based
Root Growth Optimizer	RGO	He et al	2015	Bio-inspired
Root Tree Optimization Algorithm	RTO	Labbi et al	2016	Nature-inspired
Runner-Root Algorithm	RRA	Merrikh-Bayat	2015	Bio-inspired
S				
Salp Swarm Algorithm	SSA	Mirjalili et al	2017	Swarm-based
Saplings Growing Up Algorithm	SGuA	Karci and Alatas	2006	Swarm-based
Satin Bowerbird Optimizer	SBO	Samareh Moosavi and Khatibi Bardsiri	2017	Nature-inspired
Scatter Search Algorithm	SS	Glover	1977	Evolutionary-based
The Scientific Algorithms	SAs	Felipe et al	2014	Nature-inspired
See-See Partridge Chicks Optimization	SSPCO	Omidvar et al	2015	Nature-inspired
Seeker Optimization Algorithm	SOA	Dai et al	2006	Nature-inspired
Self-Organizing Migrating Algorithm	SOMA	Zelinka	2004	Evolutionary-base
Seven-Spot Ladybird Optimization	SLO	Wang et al	2013	Bio-inspired
Shark Smell Optimization	SSO	Abedinia et al	2014	Bio-inspired
Sheep Flocks Heredity Model	SFHA	Nara et al	1999	Evolutionary-based
Shuffled Complex Evolution	SCE	Duan et al	1993	Evolutionary-based
Shuffled Frog Leaping Algorithm	SFLA	Eusuff and Lansey	2003	Bio-inspired
Shuffled shepherd optimization algorithm	SSOA	Kaveh and Zaerreza	2020	Swarm-based

Table 5 (continued)

Algorithm	Acronym	Author	Year	Class
Simplex Algorithm	SA	Pedroso	2007	Nature-inspired
Simulated Annealing	SA	Kirkpatrick et al	1983	Nature-inspired
Sine Cosine Algorithm	SCA	Mirjalili	2016	Nature-inspired
Slime Mold Algorithm	SMA	Monismith and Mayfield	2008	Bio-inspired
Small-World Optimization Algorithm	SWOA	Du et al	2006	Nature-inspired
Soccer Game Optimization	SGO	Purnomo and Wee	2013	Evolutionary-based
Social Cognitive Optimization	SCO	Xiao-Feng et al	2002	Population-based
Social Emotional Optimization Algorithm	SEOA	Xu et al	2010	Bio-based
Social Spider Optimization	SSO	Cuevas et al	2013	Swarm-based
Society and Civilization Algorithm	SCA	Ray and Liew	2003	Bio-inspired
Sonar Inspired Optimization	SIO	Tzanetos and Dounias	2017	Nature-inspired
Space Gravitational Optimization	SGO	Hsiao et al	2005	Nature-inspired
Sperm Motility Algorithm	SMA	Raouf and Hezam	2017	Bio-inspired
Sperm Whale Algorithm	SWA	Ebrahimi and Khamehchi	2016	Population-based
Sperm Swarm Optimization Algorithm	SSO	Shehadeh and Ahmedy	2018	Bio-inspired
Spider Monkey Optimization	SMO	Bansal et al	2014	Swarm-based
Spiral Optimization Algorithm	SOA	Jin and Tran	2010	Nature-inspired
Spiral Dynamics Inspired Optimization	SDOA	Tamura and Yasuda	2011	Nature-inspired
Spotted Hyena Optimizer	SHO	Dhiman and Kumar	2017	Bio-inspired
Squirrel Search Algorithm	SSA	Jain et al	2019	Nature-inspired
States Matter Optimization Algorithm	SMOA	Cuevas et al	2014	Nature-inspired
Stem Cells Algorithm	SCA	Taherdangkoo et al	2011	Bio-inspired
SuperBug Algorithm	SbA	Anandaraman et al	2012	Evolutionary-based
Stochastic Fractal Search	SFS	Salimi	2015	Evolutionary-based
Stochastic Search Network	SSN	Bishop	1989	Nature-inspired

Table 5 (continued)

Algorithm	Acronym	Author	Year	Class
Strawberry Algorithm	SBA	Merrikh-Bayat	2014	-
Swallow Swarm Optimization Algorithm		Neshat et al	2013	Swarm-based
Swarm-Inspired Projection Algorithm	SiPA	Su et al	2009	Swarm-based
Swine Influenza Models Based Optimization	SIMBO	Pattnaik et al	2013	Bio-inspired
Symbiotic Organisms Search	SOS	Cheng and Prayogo	2014	Swarm-based
Synergistic Fibroblast Optimization	SFO	Subashini et al	2017	Bio-inspired
T				
Tabu Search Algorithm	TS	Glover	1986	Population-based
Teaching–Learning Based Optimization	TLBO	Zhang et al	2011	Population-based
Team Game Algorithm	TGA	Mahmoodabadi	2018	Evolutionary-based
Termite Colony Optimization	TCO	Hedayatzadeh et al	2010	Population-based
Termite-hill Algorithm	ThA	Zungeru et al	2012	Nature-inspired
Tree Growth Algorithm		Cheraghalipour et al	2018	Bio-inspired
Tree Physiology Optimization	TPO	Hanif	2017	Bio-inspired
Tree Seed Algorithm	TSA	Kiran	2015	Population-based
Thermal Exchange Optimization	TEO	Kaveh and Dadras	2017	Nature-inspired
Tug of War Optimization	TWO	Kaveh and. Zolghadr	2016	Nature-inspired
U				
Unconscious Search	US	Ardjmand and Amin-Naseri	2012	Nature-inspired
V				
Variable Mesh Optimization	VMO	Puris et al	2012	Population-based
Variable Neighborhood Descent Algorithm	VND	Mladenović and Hansen	1997	Bio-inspired
Vibrating Particles System	VPS	Kaveh and Ghazaan	2017	Nature-inspired
Viral Search	VS	Cortés et al	2008	Bio-inspired
Virus Colony Search	VCS	Li et al	2016	Bio-inspired

Table 5 (continued)

Algorithm	Acronym	Author	Year	Class
Virus Optimization Algorithm	VOA	Liang and Cuevas Juarez	2016	Bio-inspired
Volleyball Premier League Algorithm	VPLA	Moghdani and Salimifard	2018	Evolutionary-inspired
Vortex Search Algorithm	VSA	Doğan and Olmez	2015	Nature-inspired
W				
Wasp Swarm Optimization	WSO	Pinto et al	2005	Swarm-based
Water Cycle Algorithm	WCA	Eskandar et al	2012	Nature-inspired
Water Evaporation Optimization	WEO	Kaveh and Bakhshpoori	2016	Nature-inspired
Water-Flow Algorithm	WFA	Yang and Wang	2007	Nature-inspired
Water strider algorithm	WSA	Kaveh and Dadras Eslamlou	2020	Nature-inspired
Water Wave Optimization	WWO	Zheng	2015	Nature-inspired
Whale Optimization Algorithm	WOA	Mirjalili and Lewis	2016	Nature-inspired
Wind Driven Optimization	WDO	Bayraktar et al	2010	Swarm-based
Wingsuit Flying Search	WFS	Covic and Lacevic	2020	Nature-inspire
Wisdom of Artificial Crowds Algorithm	WoAC	Yampolskiy and El-Barkouky	2011	Nature-inspired
Wolf Colony Algorithm	WCA	Liu et al	2011	Nature-inspired
Wolf Search Algorithm	WSA	Tang et al	2012	Swarm-based
Worm Optimization	WO	Arnaout et al	2014	Swarm-based
Y				
Yin-Yang Pair Optimization	YYPO	Punnathanam and Kotecha	2016	Population-based
Z				
Zombie Survival Optimization	ZSO	Nguyen and Bhanu	2012	Swarm-based

here for easy summary. For each metaheuristic algorithms, Table 5 lists their authors, class of metaheuristic and published year.

9 Conclusion

In general, several metaheuristic techniques that are available in the literature appears to be very popular and have been proven beyond reasonable doubt to be efficient in solving complex real-world problems. It is noteworthy to mention here also that these approximate solution methods are considered to be tremendously fascinating research area with high significant practical ramifications. It is equally true to say that because optimization problems abound in nature and are certainly embedded in our day to day life experiences, the area of metaheuristics research has drawn a lot of curiosity and enthusiasm specifically among young researchers who continuously to explore their surroundings for possible inspirational source that might lead to the formulation of new and efficient metaheuristic algorithms. On the one hand, because mother nature in itself is very complex and diverse, the source of inspiration for metaheuristic design and development also appears to be very diverse and consequently the resulting proposed metaheuristic algorithms to date are likewise enormous. In fact, our earlier study reveals that there are over 200 metaheuristic techniques available in the literature and virtually every month there is at least one or more new algorithms released to the scientific community and the counting is still ongoing.

Obviously, the recorded successes of some standard metaheuristic techniques reported in the literature can be attributed to the steep increase in the cumulative number of the basic and variants of the metaheuristics proposed over the last decades. More so, the proliferation of literature in this research domain has equally made it extremely difficult and confusing for interested researchers and the scientific community to easily identify novel research trends and challenges with practical bearing. In the past, just very few study have been dedicated towards identifying and classifying some of the existing metaheuristic techniques. Similarly, some other related studies have equally attempted to create a complete taxonomy of all the published metaheuristics for the easy of identifying strengths, weaknesses and possible application areas of the global optimization metaheuristic methods. However, despite these audacious and noble attempt to provide a comprehensive classification and taxonomy, little or no success have so far been achieved in this undertaking over the years. The reason for this unsuccessfulness can be completely tied to the fact that the listing of the metaheuristic appears to be endless for now, especially with the proposal and arrival of new metaheuristic on a monthly basis.

In this study we have holistically ventured into collating the general algorithmic profiles of over 250 metaheuristic algorithms in terms of design inspirational source, classification based on swarm or evolutionary search concept, existing variation from the original design, and application areas. Similarly, the bibliometric analysis of the field of metaheuristic was critically examined. Further, we successfully presented a more comprehensive and relatively new taxonomic classification list of both classical and new generation sets of metaheuristic algorithms available in the literature, with the aim of providing an easily accessible collection of popular optimization tools for the global optimization research community who are at the forefront in utilizing these tools for solving complex and difficult real-world problems. However, even though several similar research attempt have been previously established as aforementioned earlier, the current study does not in any way claim any completeness in its own endeavor. This is because it is difficult to provide a complete taxonomy of optimization methods since optimization itself has many subfields with multiple links. We hope that the overall overview and the detailed classifications of all the available up-to-date state-of-the-art and new generation metaheuristic techniques presented in this study will inspire further novel research in the field of global optimization methods and subsequently provide better insight into future designs of more practicable metaheuristic algorithms that would be capable of handling complex and large-scale real-world problems.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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