INDERSCIENCE PUBLISHERS
Linking academia, business and industry through research

International Journal of Bio-Inspired Computation

ISSN online: 1758-0374 - ISSN print: 1758-0366
https://www.inderscience.com/ijbic

Bio-inspired algorithms for cybersecurity - a review of the state-of-the-art and challenges

Kwok Tai Chui, Ryan Wen Liu, Mingbo Zhao, Xinyu Zhang

DOI: 10.1504/IJBIC.2023.10048934

Article History:
Received: 31 January 2022
Accepted: 13 June 2022
Published online: 22 January 2024

Copyright © 2024 Inderscience Enterprises Ltd.

Bio-inspired algorithms for cybersecurity – a review of the state-of-the-art and challenges

Kwok Tai Chui*

Department of Electronic Engineering and Computer Science,
School of Science and Technology,
Hong Kong Metropolitan University, Hong Kong
Email: jktchui@hkmu.edu.hk
*Corresponding author

Ryan Wen Liu

Hubei Key Laboratory of Inland Shipping Technology,
School of Navigation,
Wuhan University of Technology,
Wuhan 430063, China
Email: wenliu@whut.edu.cn

Mingbo Zhao

School of Information Science and Technology,
Donghua University,
Shanghai 200051, China
Email: mzhao4@dhu.edu.cn

Xinyu Zhang

Navigation College,
Dalian Maritime University,
Dalian 116026, China
Email: zhangxy@dlmu.edu.cn

Abstract: It is witnessed that the popularity of the research in cybersecurity using bio-inspired algorithms (a key subset of natural algorithms) is ever-growing. As an emergent research area, researchers have devoted efforts to applying and comparing various bio-inspired algorithms to cybersecurity applications. It is necessary to have a systematic review of bio-inspired algorithms for cybersecurity to fill the gap in the missing research study on this topic. The research contributions of this review article are four-fold. It first highlights the foundation of the baseline and latest development of 12 popular bio-inspired algorithms in three categories namely ecology-based, evolutionary-based and swarm intelligence-based algorithms. A systematic review is conducted to synthesise and compare the research methodologies, results and limitations. In-depth discussion will be made on the shortlisted and highly cited articles. The tips to select appropriate algorithm or the combination of multiple algorithms have been reported, along with the pros and cons on the design and formulations. Future research directions will be presented to meet the trends and unexplored research.

Keywords: bio-inspired algorithms; cybersecurity; ecology-based algorithm; machine learning; evolutionary algorithms; multi-objective optimisation; swarm intelligence; trade-off solution.

Reference to this paper should be made as follows: Chui, K.T., Liu, R.W., Zhao, M. and Zhang, X. (2024) 'Bio-inspired algorithms for cybersecurity – a review of the state-of-the-art and challenges', *Int. J. Bio-Inspired Computation*, Vol. 23, No. 1, pp.1–15.

Biographical notes: Kwok Tai Chui received his BEng in Electronic and Communication Engineering – Business Intelligence minor and PhD from City University of Hong Kong. He had industry experience as a Senior Data Scientist in internet of things (IoT) company. He is with the Department of Technology, School of Science and Technology, at Hong Kong Metropolitan University as an Assistant Professor. He has more than 90 research publications including edited books, book chapters, journal papers, and conference papers. His research interests include computational intelligence, data science, energy monitoring and management, intelligent transportation, smart metering, healthcare, machine learning algorithms and optimisation.

Copyright © 2024 Inderscience Enterprises Ltd.

Ryan Wen Liu received his BSc (Honours) in Information and Computing Science from the Department of Mathematics, Wuhan University of Technology, Wuhan, China, in 2009, and PhD in Mathematical Imaging from The Chinese University of Hong Kong, Hong Kong, in 2015. He was a Visiting Professor with the Agency for Science, Technology and Research, Singapore. He is currently an Associate Professor with the School of Navigation, Wuhan University of Technology, and Visiting Scholar with College of Computer Science and Software Engineering, Shenzhen University, Shenzhen, China. His research interests include mathematical imaging, computer vision, trajectory data mining and computational navigation sciences.

Mingbo Zhao received his PhD in Computer Engineering from the Department of Electronic Engineering, City University of Hong Kong, Kowloon, Hong Kong S.A.R., in Jan. 2013. After that, he also worked in the City University of Hong Kong as a postdoctoral researcher. He is currently a Full Professor in the Donghua University, Shanghai, China. He has authored or co-authored over 120 technical papers published at prestigious international journals and conference. His current research interests include pattern recognition and machine learning.

Xinyu Zhang is a Professor at the Navigation College of Dalian Maritime University. He is appointed as one of the first special researchers by the China Institute of Navigation and member of Institute of Marine Engineering, Science & Technology. He is an author of more than 50 papers published in international journals and has more than 20 patents. His main research interests are vessel traffic organisation optimisation, maritime big data application and intelligent navigation of unmanned ships.

1 Introduction

The world is moving towards the smart city vision to enhance the sustainability and resilience. In 2015, members in the United Nations have established global partnership to meet 17 Sustainable Development Goals (SDGs) which are divided into 169 targets within 15 years (United Nations, 2015). Responding to the agenda in two years later, European Union published a document about how digital services and technologies could help to achieve SDGs (European Union, 2017). Attention is drawn to cybersecurity which contributes to SDGs 4, 8, 9, and 16 by offering a peaceful, resilient, free and open cyberspace. The status report in 2020 revealed that most of the SDGs are far on track (Carlsen and Bruggemann, 2021).

Recent review-type articles have conducted surveys for cybersecurity in various aspects such as deep learning (Dixit and Silakari, 2021), machine learning (Handa et al., 2019), generative adversarial network (Yinka-Banjo and Ugot, 2020), blockchain (Liu et al., 2021b), internet of things (Chui et al., 2022), evolutionary algorithms (Kusyk et al., 2018), in-vehicle network (Xie et al., 2021), social media (Herath et al., 2022) and surveillance system (Chui et al., 2019).

To the best of our finding, the last review article in bio-inspired algorithm for cybersecurity was published in 2018 where the data query was up to 2017 (Rauf, 2018). To reflect the development of bio-inspired algorithms for cybersecurity in recent research works (refer to Figure 2 for significant growth in the number of publications in recent years), a systematic review is conducted to fill the gap of a missing latest review on the bio-inspired algorithms for cybersecurity. There are other review articles that focused on certain applications such as cloud security (Ahsan et al., 2020), network security (Saleem et al., 2020) and phishing attack (Jain and Gupta, 2022). Taking the advantages of the biological mechanisms of the algorithms, the design and formulations are easier, and more likely to match the general behaviours of the system model.

1.1 Research contributions

The research contributions of this review paper are summarised as follows.

1 Highlight the fundamental and latest development of 12 bio-inspired algorithms.

2 Systematic review on the bio-inspired algorithms for cybersecurity applications. Critical analysis and summary of the methodology, results, and limitations of existing are discussed.

3 Study and analyse the highly cited articles to drive most impactful research.

4 Recommend future research directions and unexplored research topics.

1.2 Organisation of the paper

The organisation of this paper is illustrated as follows. Section 2 presents with the categorisation of bio-inspired algorithms, that is followed by the basic principles and latest development of 12 bio-inspired algorithms. A systematic review on the bio-inspired algorithms for cybersecurity applications is carried out in Section 3. In Section 4, a thorough study and analysis is made on the highly cited articles shortlisted from the article search. The future research directions to address the existing limitations and unexplored research topics are suggested in Section 5. At last, the paper is ended with conclusions in Section 6.

2 Categorising and overviewing the latest development of bio-inspired algorithms

2.1 Categories of bio-inspired algorithms

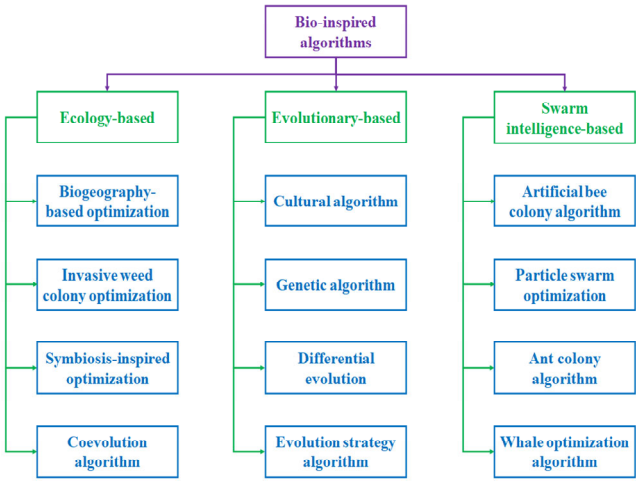
Bio-inspired algorithms can be classified into three categories namely ecology-based, evolutionary-based and swarm intelligence-based algorithms. Ecology-based algorithms are algorithms refer to the interactions in intraspecies (within species) and interspecies (between species). Typically, these algorithms utilise techniques such as symbiosis, biogeography, and colonisation. In regard to the evolutionary-based algorithms, the mechanism is based on biological evolution, including the major steps in selection, mutation, reproduction, and combination. By contrast, the swarm intelligence-based algorithms consider a group of agents which interact with the others and environment. Figure 1 shows 12 famous algorithms in these categories. To balance the discussion in each category, equal number of approaches (four) is chosen where details will be shared in Section 2.2. The selected 12 algorithms are:

1 ecology-based algorithms: biogeography-based optimisation (BBO), invasive weed colony optimisation, symbiosis-inspired optimisation and coevolution algorithm (CEA)

2 evolutionary-based algorithms: cultural algorithm (CA), genetic algorithm (GA), differential evolution (DE) and evolution strategy (ES) algorithm

3 swarm intelligence-based algorithms: artificial bee colony (ABC) algorithm, particle swarm optimisation (PSO), ant colony algorithm and whale optimisation algorithm (WOA).

Figure 1 Categories of bio-inspired algorithms and selected approaches (see online version for colours)



2.2 Overview and latest development of bio-inspired algorithms

To provide an in-depth discussion on the latest development of bio-inspired algorithms, the topics of interest are not limited in Section 2.2.

2.2.1 Ecology-based algorithms

2.2.1.1 Biogeography-based optimisation

Inspired by the evolution of new species, the migration of species between islands, and the extinction of species, BBO was proposed by Simon (2008). There are two key characteristics:

1 habitat suitability index: whether the island is a good habitat

2 suitability index variable: also known as features that relate to the habitat suitability index.

Typical features are temperature, land space, topographic and vegetative diversity, and rainfall. Owning to the fact that BBO does not have a pre-requisite of differentiable function, it can be applied to discontinuous function and thus flexible to a wide range of optimisation problems.

Since then, many variants of BBO have proposed to improve the baseline method and customise to various daily life applications. In Chen et al. (2016), the migration of species between islands was modelled with covariance matrix in order to reduce the dependence of algorithm performance on the coordinate system. Another work proposed by Zhao et al. (2019) introduced a two-step differentiation in the migration process. The diversity was maintained whereas the convergence was enhanced. A recent work (Ahirwar et al., 2021) modified the BBO by introducing chaos theory to assist the data distribution with information entropy and enhance the population initialisation and convergence rate with chaotic theory. An et al. (2021) has proposed four schemes to enhance the performance of BBO, including the modifications of the mutation operator, the migration operation, and the habitat suitability index, storing sub-optimal solutions with elite storage strategy, enhancing the local search ability with hybrid variable neighbourhood search, and enhancing the convergence rate with V-dominance principle. BBO can also be applied to visual object tracking which can be integrated to face ID detection system to verify the truth users (Daneshyar and Charkari, 2022). This enhances the accuracy and efficient of the detection model. For low-light environment, L0-norm gradient sparsity and structure-aware regularisation could be applied to reduce the noise level of images (Guo et al., 2020) and a three-stage dehazing network with deep network could be applied (Liu et al., early access).

2.2.1.2 Invasive weed colony optimisation

The first version of the invasive weed (colony) optimisation (IWO) was initiated by Mehrabian and Lucas (2006). IWO is characterised by:

1 high robustness and most troublesome plants in agriculture

2 good adaptation with environment and behave to fit for different conditions

3 reproduction may perform rapidly with and without sex cells.

In general, to solve the optimisation problem, IWO takes less iteration compared with PSO in handling multi-dimensional functions.

Various research works have presented improved IWO algorithms with extensive analysis to confirm their effectiveness. Zheng et al. (2020b) incorporated Lévy flight algorithm and random mutation to improve the efficiency and the balance between exploitation and exploration of the IWO. To improve the balance between exploitation and exploration, another work (Zheng et al., 2020a) has suggested the inclusion of row and selective crossover, and random mutation. Chaos theory and Bezier curve with the aid of beginning angle of turning, were used to improve the IWO in Kashyap et al. (2021). It is possible to restructure IWO as discrete IWO, demonstrated in Şimşir and Taşpınar (2021). A fewer number of searches can be achieved by partial transmit sequence. This had benefit to the enhancement of peak-to-average power ratio in the universal filtered multicarrier problem. A quantum-based IWO algorithm was proposed for the task scheduling problem in cyber-physical system (Neelakandan et al., 2022). It aims at assigning M autonomous tasks to N distinct resources in order to reduce the time and computational complexity, which in turn reducing the energy consumption.

2.2.1.3 Symbiosis-inspired optimisation

This is also known as symbiotic organisms search (SOS), proposed by Cheng and Prayogo (2014). An extensive discussion on the formulations and performance verification were made with 26 mathematical scenarios and five engineering problems. In general, SOS is a simulation on the survival and propagation between any two distinct species via symbiotic interaction strategy in an ecosystem. There are three typical types of symbiotic dependencies namely parasitism, commensalisms and mutualism. The key characteristics of SOS made use of these dependencies as the working principle.

SOS has received much attention in recent years. Tejani et al. (2019) proposed three strategies namely normal line method, modified parasitism, and adaptive mutualism, for the classification of future population generation, the enhancement of parasitism, and the balanced of search space for exploitation and exploration, respectively. Another work (Çelik, 2020) adopted quasi-oppositional learning and piecewise linear chaotic map for the enhancement of the quality of solutions, and convergence rate, respectively. To address the issues of premature convergence, and inefficient exploration search, the modification of mutualistic equations, and the adoption of lower combination rates in parasitic equations were proposed (Tsai, 2021). Besides premature convergence, poor diversity and inability in achieving global optimal solutions are key limitations in traditional SOS. To tackle with these issues, the inter-group and multi-group communication schemes using quantum-based behavioural model were introduced (Chu et al., 2020). In today's era, the complexity of the optimisation problem is ever-growing that often requires to solve a high dimensional problem. Chakraborty et al. (2022) proposed an enhanced SOS approach that featured three key components:

1 parasitism phase was designed to reduce the computational overhead

2 explored and exploited the research region using benefit and mutual factors

2 apply nonlinearity to the benefit factor.

Alternatively, it is also possible to reduce the dimensionality of the dataset to lower dimension via subspace segmentation (Cheng et al., 2017).

2.2.1.4 Coevolution algorithm

More than 30 years ago, CEA was proposed (Hillis, 1990). The rationale was to introduce a simulated evolutional scheme to address practical optimisation. Differed to the real-life evolution, the simulated evolution assumes idealisation in a biological system. The coevolving characteristic helps to enhance the parasitism phase and thus evolutionary computation. To avoid obtaining local optimal solutions, Hillis (1990) ensured the individual population resided within a certain spatial grid.

Wu et al. (2021) enhanced the CEA by three strategies including:

1 first-come-first heuristic-based flow line scheduling

2 seru scheduling based on distribution estimation

3 seru formulation based on sub-space exploitation.

Considering the issue of the dimensionality, two spaces were defined for individual evolution and pattern evolution for better fitness and groupings, respectively (Ge et al., 2020). To leverage the diversity in the objective space and decision space simultaneously, Wang et al. (2021a) proposed fitness assignment and dual-diversity archive update schemes. Deng et al. (2021a) stressed the limitations of traditional CEA in high search stagnation possibility, slow convergence speed, poor diversity in a long search and ineffective solutions. A proposal of divide-and-conquer and quantum theory were introduced as a new potential solution to address the four issues at once (Wang et al., 2021c). A hybrid CEA and GA algorithm was proposed to solve the optimisation problem in both dynamic and static channel

power optimisation of network (Vejdannik and Sadr, 2022). The signal-to-noise ratio was improved by at least 2.4 dB.

2.2.2 Evolutionary-based algorithms

2.2.2.1 Cultural algorithm

Reynolds et al. (2011) proposed the CA in two decades ago. To start with, defining the belief space as an extension to GA. In each iteration, the best group of individuals of the population (based on the fitness values) helps the update of the belief space. There are five main categories of the belief space related to the spatial knowledge for search space topology, temporal knowledge for the search space history, situational knowledge for the information of important events, domain specific knowledge for the domain information, and normative knowledge for the series of ranges of individuals.

When it comes to the improved variants of CA (Shah and Kobti, 2020), the possibility of the adoption of hybrid categories of the belief space using situational knowledge and normative knowledge was revealed. Another work (Mao and Liu, 2022) had utilised four categories including normative knowledge, situational knowledge, temporal knowledge and spatial knowledge. In Gao et al. (2021), CA was extended with fireworks algorithm and quantum theory to reduce the computational complexity and enhance the convergence rate. To enhance and balance the search space between exploitation and exploration, Al-Gharaibeh et al. (2021) adopted enhanced Levy flight search to guide the search. A hybrid CA and PSO was proposed to further enhance the convergence rate (Kaveh et al., 2021) where its effectiveness was confirmed by 23 benchmark datasets across different applications.

2.2.2.2 Genetic algorithm

GA is the most famous evolutionary-based algorithm with a long history proposed in 1960 where it started to become popular since 1990s (John, 1992). Inspired by the Charles Darwin's theory of natural evolution, the individuals will be chosen and moved to the next generation for reproduction following the process of natural selection. Crossover and mutation are the two most important genetic operators in GA. The basic strategy is to fine-tune the population size, crossover rate, and mutation rate for better optimal solutions.

Many of the latest variants of GA were inspired by the non-dominated sorting genetic algorithm II (NSGA-II) (Deb et al., 2002) and non-dominated sorting genetic algorithm III (NSGA-III) (Deb and Jain, 2013; Jain and Deb, 2013) which were the most highly cited approaches among numerous versions of GA. To enhance the problem specific distribution, convergence rate, and selection, adaptive crossover and congestion strategies were introduced (Deng et al., 2022). An extra operator namely accuracy-preferred domination operator was included to ensure better selection of individuals that yielded higher accuracy (Zhou et al., 2021). To reduce memory loading and evolutionary time, particularly in a complex problem, uniform cumulative distribution function and uniform probability density function were suggested as effective solutions (Jiang and Xue, 2021). GA is also useful in optimally joined multiple algorithms (Chui et al., 2021). A hybrid GA and ant colony optimisation (ACO) algorithm was proposed for task scheduling in cloud data centre (Ajmal et al., 2021). Compared with stand-alone GA algorithm, the hybrid approach was taking advantages in the reduction of time complexity in response time and workflow execution time, as well as the storage in scheduling solution space.

2.2.2.3 Differential evolution

Proposed in 1996 (Price) and refined in 1997 (Storn and Price), the DE aimed at the minimisation of the non-differentiable and nonlinear functions bounded by a continuous search space. Mainly, it is formulated with real numbers. Therefore, DE has some limitations in applying to combinatorial, and discrete optimisation problems that require further customisation (Pant et al., 2020). Iteration is performed on the agents to improve the solution, typically if the position of the agents helps in the improvement of the solution, based on the fitness functions and values, the agents are retained.

An adaptive distributed DE (Zhan et al., 2019) was proposed to enhance the selections of strategy and setting of hyperparameters. Co-evolution with master-slave distributed scheme was performed on the balance population, exploitation population and exploration population. To optimally design the control parameters and select mutation strategies, the work (Deng et al., 2021b) not only introduced wavelet basis function but also merged five mutation strategies. In Zhang et al. (2020a), three new schemes:

1 non-dominated sorting operator with crowding distance for time consumption reduction on the selection operator

2 one-bit purifying search operator for self-learning of elite individuals

3 binary mutation operator using probability difference for the guidance and movement of individuals towards the optimal areas.

The improve the convergence rate and accuracy, migrating variables were introduced to supplement DE (Zou and Gong, 2022). In detail, repairing scheme to assist the movement of solutions, replacement of segments in the mutant vectors by old target, and introduction of attracting factor into mutation operator, were proposed. The robustness and convergence rate of the internet-of-things network were enhanced by an adaptive enhanced DE (Qureshi et al., 2022). It enhanced the convergence rate by 7%–42% compared with three optimisation algorithms.

2.2.2.4 ES algorithm

ES was inspired by the concept of evolution. It was formally defined in 1965 (Rechenberg). The key characteristics involved:

1 representing by natural selection problem

2 searching space with real numbers

3 search operators using mutation and environmental selection

4 monotonic transformation of the objective function.

Typically, various strategies namely natural ES, covariance matrix adaption ES, and Gaussian ES will be adopted for daily life applications.

The advent of technological development in computer science has driven various proposals to enhance the baseline ES algorithm. A covariance matrix adaption ES was applied to ES to enhance the ability of global search (Maki et al., 2020). Besides the adoption of the same strategy, another work (Kumar et al., 2022) proposed a Broyden-based mutation strategy to replace inappropriate solutions with more appropriate solutions. Nonlinear equality and inequality constraints were considered. Zhang et al. (2021) proposed a new formulation to start with small population size and niching strategy in the decision space to enhance the set of Pareto-optimal solutions. In addition, the ES can be improved by repelling subpopulations and covariance matrix self-adaptation (Ahrari et al., early access). This approach has made improvement in the areas of the initialisation of subpopulation, the treatment of infeasible solutions, the covariance matrix of the stopping criteria of the subpopulations, and the distance of the solutions. It is often to perform the optimisation algorithm on a cloud-edge manner to meet the requirement of computational power and time-critical applications. An ES approach was proposed to minimise the energy consumption, load imbalance and makespan (Li et al., 2022a). It outperformed three existing works based on the performance evaluation and analysis with benchmark datasets.

2.2.3 Swarm intelligence-based algorithms

2.2.3.1 ABC algorithm

The ABC algorithm was proposed in 2005 (Karaboga). The basic principle is highlighted as follows. The location of food source indicates the possibility of the solutions of the optimisation. The number of food source is correlated to the fitness of the solution. The number of solutions in the population equals to the number of employed bees. Besides the employed bees, the onlooker bees will evaluate the information based on all employed bees. The number of sources will be utilised to determine the type of food source. The third type of bees (scout bees) will be translated from a few employed bees, which abandoned their food sources and searched new food sources.

A neighbourhood radius selection scheme was introduced to replace the existing probability selection in Wang et al. (2020). This could address the issue of traditional approach that two distinct solutions are difficult to be distinguished. To enhance the optimisation capability such as balancing the exploitation and exploration of the search space, knowledge fusion was employed to improve ABC (Wang et al., 2021b). Another work (Alrosan et al., 2021) balanced the search spaces with the aid of an updated search equation from the mean of the previous best solutions. Three kinds of knowledge along with the utilisation methods were presented. Extensive analysis using 32 benchmark datasets was conducted to reveal the effectiveness of the proposed method. In Li et al. (2020), three schemes were proposed:

1 solution update technique

2 greedy iterative strategy

3 factory assignment rule.

The encryption process in the biomedical systems was enhanced by ABC to improve the security of the cryptography model (Ahmed et al., 2022). The algorithm has two benefits in the leverage of security and time reduction for biomedical systems.

2.2.3.2 Particle swarm optimisation

PSO is the most popular swarm intelligence-based algorithm. In many papers, researchers brought the attention to compare PSO with GA. PSO was originated in the research work (Kennedy and Eberhart, 1995). In PSO, the analogy of population and candidate solutions becomes swarm and particles, respectively. Some basic formulations are initiated for the movement of particles around a search space. Typically, the movement of particles depends on the best-known position of overall population and individual particle.

Some variants of PSO are discussed. In Zhang et al. (2020b), a competition scheme was introduced to improve the performance of the PSO. Besides, results have demonstrated that the diversity can be enhanced by dynamic neighbourhood-based learning scheme. When it comes to an optimisation problem that owns both discrete and continuous decision variables (Wang et al., 2021b), PSO should be modified, for instance, with mixed-variable encoding scheme so that these two types of variables can be managed at the same time. It is worth noting that PSO is unable to handle constrained optimisation problem. A tailor-made constraint handling method was proposed (Ang et al., 2020) to assist the population searching. Hybrid evolution phases were introduced to support multiple search operators. Probabilistic mutation operator and multi-swarm technique as of the maintenance schemes of diversity, were incorporated into the PSO to avoid premature convergence. Considering Sedighizadeh et al. (2021), four innovative approaches were proposed. They are the dynamic inertial weight adjustment scheme, position and velocity update via stronger mechanism, search space enhancement by effective exploration scheme, and robust interrelation between particles. A PSO-based deep belief network was presented

to extend a binary intrusion detection problem to five-class (Sajith and Nagarajan, 2022). It achieved accuracy of more than 96% and outperformed three existing approaches.

2.2.3.3 ACO algorithm

Introduced in 1991 (Colorni et al), the ACO algorithm simulates the ants for localising optimal solutions. In reality, when the ants explore the environment, they communicate with the others using pheromone-based communication. This is analogised to simulated ants who record the positions (solutions).

In Paniri et al. (2020) discussed the usefulness of normalised cosine similarity between class labels and features in the enhancement of convergence rate. Also, supervised and unsupervised-based heuristic functions were introduced to enhance the relevancy (equivalent to the reduce of redundancy). Another work (Zhao et al., 2021) focused on the enhancement of convergence rate and quality of the solutions by incorporating vertical and horizontal crossover searches and improving the selection mechanism. To balance the search space between exploration and exploitation, Liu et al. (2021a) adopted Levy flight and epsilon greedy algorithms as of pseudo-stochastic mechanism. With the availability of computation resources, parallelisation of ACO could increase the training speed of the optimisation problem (Peake et al., 2022). A chaotic elite ACO algorithm was proposed for quality-of-service secure problem (Li et al., 2022b). Chaos theory was applied for population initialisation to leverage the population diversity and avoiding the convergence to local optimal solutions.

2.2.3.4 Whale optimisation algorithm

As one of the recently proposed swarm intelligence-based algorithm, the WOA was firstly presented in 2016 (Mirjalili and Lewis). Here are the major points that drive the proposal of WOA:

1 human's brain and whale's brain share common cells in some areas

2 whales could live in groups or alone

3 special hunting method in humpback whales where they have tendency in hunting small fishes and school of krill that are close to the surface.

The analogy of WOA is assuming the best candidate (current) is close to the optimal solution (the target prey). The search agents will aim at moving towards the best search agent in each iteration.

An enhanced WOA algorithm was proposed with the introduction of jumping behaviour, spiral position, and adaptive search surrounding scheme (Qiao et al., 2020). Owning to the limitations in global search and convergence speed, Chen et al. (2020) introduced a double adaptive weight strategy and random replacement strategy. Similar to other bio-inspired algorithms, WOA may suffer from the issue of search spacing between exploitation and exploration. A modified mutualism phase could be added to resolve the issue (Chakraborty et al., 2021). Three limitations and solutions of WOA were discussed in Li et al. (2022b) including extension of search range by adjusting the range of initial random numbers, enhancement of self-adjusting ability by combination of cooperative convergence factor and variable speed adjustment factor, and quality enhancement of initial population by quadratic opposition-base learning. A chaotic oppositional-based WOA was proposed to support a feed-forward neural network (Chatterjee et al., 2022). Performance analysis showed that it outperformed chaotic WOA, baseline WOA, Adam optimisation algorithm and PSO.

3 Systematic review on the bio-inspired algorithms for cybersecurity applications

3.1 Search tool

The systematic review focuses on the bio-inspired algorithms for cybersecurity applications. In view of the quality of paper, details of methodology, and thorough performance evaluation and analysis, Science Citation Index Expanded (SCIE) and Social Science Citation Index (SSCI) research articles are considered. Therefore, advanced search in the Web of Science is utilised as the research engine to obtain relevant articles in the research topic. The query was made on January 2022.

3.2 Search strategy

The following strategies apply to the advanced search:

1 Study period is from 2010 to 2021.

2 Language of articles is restricted to English.

3 Only articles indexed in SCIE or SSCI are included.

4 Only document types of 'articles' is included.

5 Early access articles that are mislabelled with a year.

6 The advanced search is based on the query using field tag of 'TS = topic'.

7 Any one of the following terms must be included in TS: cybersecurity, cyberterrorism, computer security, computer crime, computer fraud, cyber, cyber security, information technology security, automotive security, IT security, internet security, mobile security network security, DDoS, denial of service, cyberattack, copy protection, malware, spamming and scareware.

It is noted that there are too many terms that could relate to the topic, however, current discussion should cover most of the articles.

8 Apart from 6, any one of the following terms must be included in the TS, which are the 12 algorithms discussed in Section 2: BBO, invasive weed colony optimisation, symbiosis-inspired optimisation, CEA, CA, GA, DE, ES algorithm, ABC algorithm, PSO, ant colony algorithm and WOA

3.3 Search results and analysis

505 articles were found by the search query. After applying the exclusion criteria, 371 articles are retained. All of the articles are indexed in the SCIE where 10 of them are also indexed in the SSCI. Before in-depth discussion on the research contents and merits of the shortlisted articles, statistics are presented on the 371 articles. Figure 2 shows the trends of the number of annual publications between 2010 and 2021 on the bio-inspired algorithms for cybersecurity applications. The number of publications before 2016 was limited (less than 20 publications). One of the major reasons is that the cost for computing resources was relatively high and cybersecurity was new topic to the public at that moment. From 2016 (16 articles) to 2021 (107 articles), the number of annual publications is increased with an average growth rate of 50.1%. There are increasing number of undergraduate and postgraduate programmes that nurture expertise in machine learning algorithms and cybersecurity, as a result more researchers are able to conduct research in the topics.

Figures 3–6 show the distribution of top 10 Web of Science categories, the top 10 publishers with largest total number of articles, the top 10 publishers with largest total number of articles and top 10 research areas. Since 46 categories were found, only the major constituents (top 10) are presented. Particularly, the top 5 categories are computer science information systems (18.3%), engineering electrical electronic (15.3%), telecommunications (14.3%), computer science artificial intelligence (7.3%), and computer science theory methods (5.5%), covering about 60% of the total. Surprisingly, it can be seen from the percentages that the research articles focused on the applications and adoptions of bio-inspired algorithms in cybersecurity applications, with limited focus on the algorithms are GA (308), PSO (188) and ant colony algorithm (59). Some of the works used multiple algorithms so that the sum of the bars in Figure 7 exceeds 371 articles. Since there is no best algorithm that fits all applications, it is common to introduce hybrid optimisation algorithms to take advantages from individual algorithms. For example, merging GA with PSO (Xie et al., 2019) and GA with ACO (Nandan and Rao, 2021).

Figure 2 Number of publications between 2010 and 2021 based on the shortlisted articles (see online version for colours)

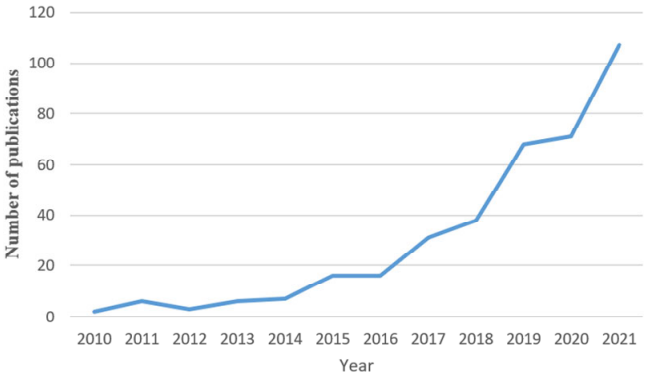


Figure 3 The distribution of top 10 Web of Science categories (see online version for colours)

Figure 4 The top 10 journals with largest total number of articles (see online version for colours)

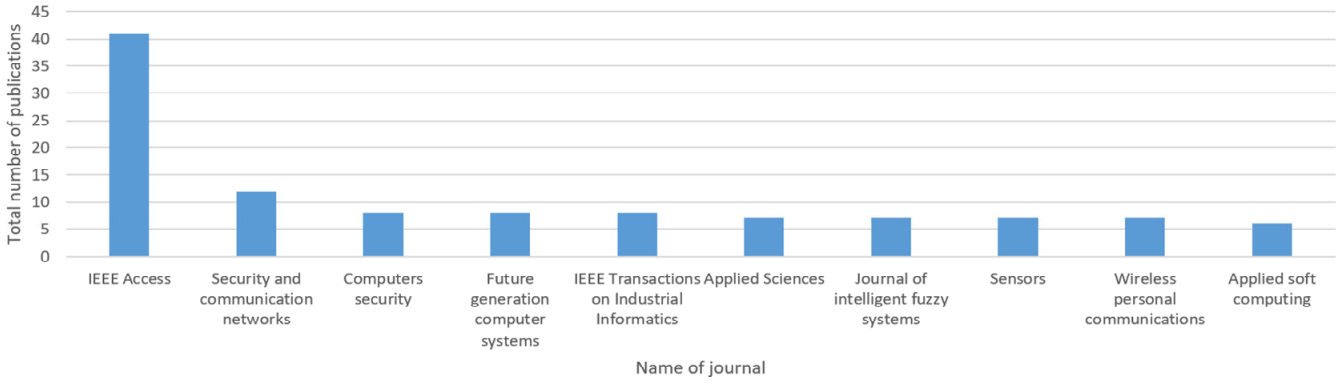


Figure 5 The top 10 publishers with largest total number of articles (see online version for colours)

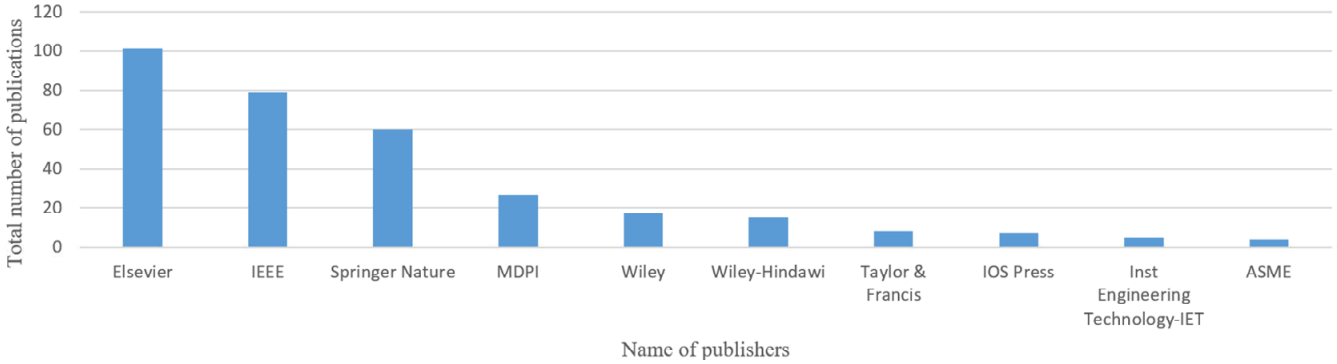


Figure 6 Top 10 research areas (see online version for colours)

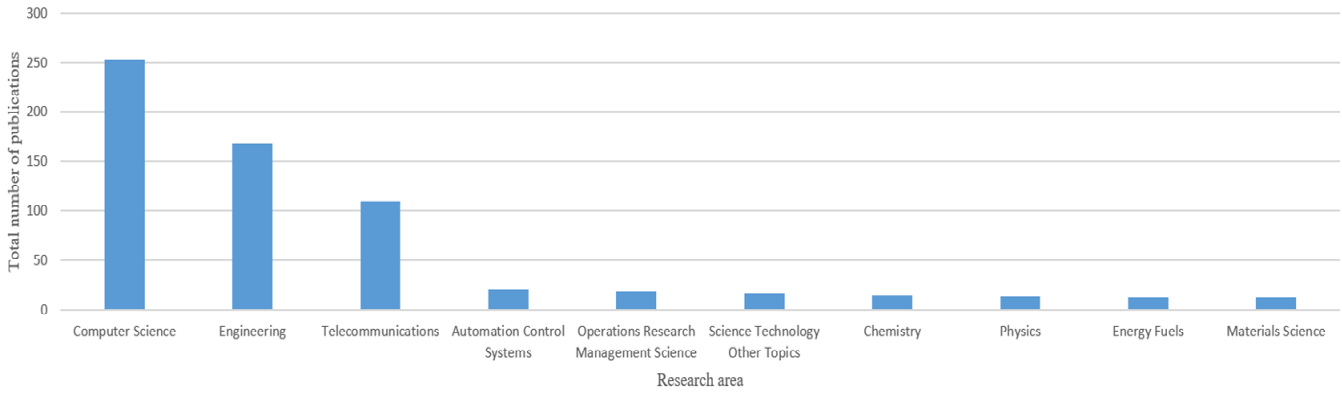
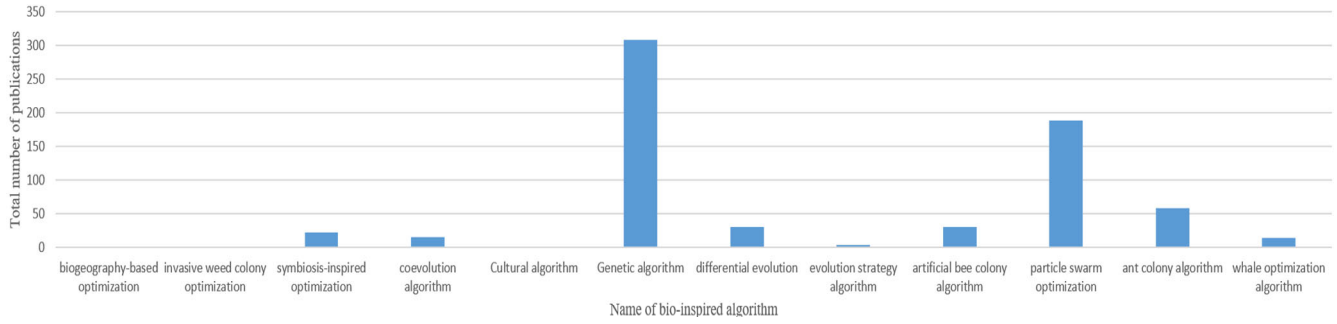


Figure 7 Total number of publications across 12 bio-inspired algorithms (see online version for colours)



4 Analysis on highly cited articles

To investigate the highly influencing articles, the top 10 highly cited articles with Web of Science citations among the 371 shortlisted articles, are discussed and summarised in Table 2. In general, the number of citations increases from research engine Web of Science, Scopus, and Google Scholar, based on the number of databases included.

In Zhan et al. (2015), cloud computing resource scheduling for cyber-physical integration using evolutionary computation algorithm was presented. Three bio-inspired algorithms ACO, GA, and PSO were used in the generic framework to solve the problem. These algorithms take advantages to contribute various parts of the scheduling problem. For examples:

1 with the consideration of an ant step as one cloud-related task, ACO extracts feasible solution more effectively

2 start with simple objective function by minimising the makespan and solving by GA, or formulating the problem as multi-objective optimisation problem

3 increase the convergence rate with various variants of PSO including renumber-based PSO, round-based, sort-based and set-based PSO.

Researchers have pointed six key challenges in the scheduling that include cloud resources, distributed and parallel, multi-objective, large-scale, adaptive dynamic and real-time scheduling.

Table 1 The number of citations of the top 10 highly cited articles

Work	*Number of citations*		
	Web of Science	*Scopus*	*Google Scholar*
Zhan et al. (2015)	252	307	447
Mishra et al. (2018)	125	170	281
Qi et al. (2020)	118	103	165
Hu et al. (2016)	106	129	141
Khammassi and Krichen (2017)	98	135	171
Kayal and Chanda (2015)	87	110	141
Biswas et al. (2018)	82	104	115
Cui et al. (2019)	79	96	111
Yi et al. (2020)	75	30	40
Karami and Guerrero-Zapata (2015)	75	100	138

Intrusion security is important to monitor a system from policy violation and malicious activity (Chaudhary et al., 2021). Typical attacks include user-to-root attacks, remote-to-local attacks, scanning attacks, and resource and bandwidth depletion attacks (a well-known example denial of service attacks). A thorough literature review was conducted to study the performance of different machine learning approaches for intrusion detections (Mishra et al., 2018). Particularly, GA and PSO were considered and demonstrated the superiority in solving various optimisation problems. Two challenges related to reinforcement learning and deep learning were discussed. Combination of these research topics as deep reinforcement learning will also be a feasible future research directions (Cvitić et al., 2022).

Cloud computing can leverage the computational power and storage of the cyber-physical systems to support a large amount of real life applications (John and Sam, 2021). Since the cloud environment is generally handling massive number of tasks, energy efficiency has received attention where a small amount of energy reduction per task will save a huge amount of energy per application. Virtual machines can be used to ensure proper resource management. To obtain optimal solution for high quality-of-service (quantified by resource utilisation, downtime, and energy consumption) virtual machine migration, NSGA-III was employed (Qi et al., 2020). Results have compared with baseline model and energy-aware virtual machine scheduling method.

A multi-objective optimisation problem was formulated to model the electricity grid and natural gas network (Hu et al., 2016). Particular, the research interest is to allow the possibility of future expansion of where and when the grid and network are expanded. To evaluate the objective function, two schemes namely point-estimate scheme and primal-dual interior-point scheme were employed. By then, NSGA-II was applied to solve the optimisation problem. Decimal coding was used to handle the integer decision variables for the candidate electricity lines, compressors and pipelines.

Network intrusion detection was considered and formulated as a classification problem in Khammassi and Krichen (2017). The work was summarised in three parts:

1 preprocessed the data with resampling, updating the values of variables, and redundant data removal

2 applied hybrid GA and logistic regression to enhance feature extraction process

3 built three decision tree classifier for network intrusion detection.

The proposal achieved almost perfect accuracy of 99.9% using benchmark dataset KDD99. A major challenge of the research is the insufficient network intrusion data where collecting positive samples are costly and not feasible in reality.

Kayal and Chanda (2015) formulated a multi-objective optimisation problem with objective functions related to the penetration constraints of solar and wind distributed generations, discrete size limit of distributed generations, and bus voltage limit. A weighted aggregation-based PSO was proposed. Typically, global optimal solution is not desired in multi-objective optimisation problem. Instead, a trade-off optimal solution is expected. In this work, strategic weight selection was employed. The experimental studies considered summer, autumn, winter, and spring with and without distributed generations, in hourly basis. Results revealed that hybrid wind and solar could produce a better benefit to the planning of distributed generations.

Apart from wind and solar, Biswas et al. (2018) also incorporated small-hydropower into the multi-objective economic-environmental power dispatch problem. To model the small-hydro power, solar, and wind, Gumbel probability density function, lognormal distribution function, and Weibull distribution function were utilised, respectively. DE algorithm was employed with the assistance of a decomposition-based EA. The performance of the proposed method outperformed baseline EA algorithm. To further enhance the performance, researches have suggested to make exploration using PSO and GA algorithms.

In Cui et al. (2019), NSGA-II was adopted to optimally design convolution neural network for malicious code detection. Researchers have discussed the effectiveness of NSGA-II in managing the nature of imbalanced malicious datasets (where malicious events are minority classes) with multi-objective formulation. Experimental results revealed that the proposed method not only enhanced the reduced loss and true positive rate, but also the accuracy and recall. Two future research directions were suggested, for example, a training model for network acceleration and time reduction, and a model for large-scale images.

The second last work (Yi et al., 2020) applied an improved ACO algorithm to perform scheduling and task optimisation of a distributed cyber-physical system. The workflow of this work is summarised as follows:

1 conducted a latest review on ACO algorithm

2 defined the existing research limitations of cyber-physical system

3 presented an improved ACO algorithm for task management

4 carried out exploration on the task optimisation and scheduling of the distributed cyber-physical system

5 conducted simulation for performance evaluation and comparison.

At last but not least, Karami and Guerrero-Zapata (2015) shared a topic on anomaly detection. PSO and K-means clustering were chosen as the techniques for a fuzzy-based anomaly detection algorithm. In general, the first metric of K-means clustering is the number of clusters, which should be optimally designed. In old days, various indexes (e.g., CH-, DB-, SH-index) were applied to determine the number of clusters. Secondly, separating the clusters is crucial to ensure a well grouping of the samples. Performance evaluation showed that the proposal made significant improvement on the area under the ROC curve, specificity, sensitivity and overall accuracy.

5 Future research directions

Inspired by the literature review and systematic analysis, several high-level ideas to drive future research directions are suggested:

1 Many bio-inspired algorithms were limited (with single digit number of published SCIE/SSCI articles) applied in cybersecurity applications including BBO, invasive weed colony optimisation, CA and ES algorithm. It is highly recommended to apply these algorithms to cybersecurity applications to look for a potential enhancement of the models.

2 Two types of bio-inspired algorithms GA and PSO have dominated the research applications in cybersecurity. A further investigation is required on whether these algorithms take superior advantages in different applications or researchers adopted the algorithms based on the convenience of accessing many technical contents.

3 Apart from computer science, engineering, and telecommunication research, it is suggested to have further exploration on the application and enhancement of algorithms towards other research areas.

4 A scalable and flexible architecture is sought for to manage ever-growing cybersecurity data. Also, computation efficient algorithms are needed because the increment of the number of data goes rapidly compared with the technological advancement of computational resources.

5 There is no best algorithm fits all applications. Hybrid algorithms should be the most convincing alternatives to capture the advantages of each algorithm.

6 Conclusions

In this paper, a latest review on the development of 12 bio-inspired algorithms in the fields of ecology-based, evolutionary-based, and swarm intelligence-based algorithms was firstly presented. Owning to the limitations of the lack of in-depth discussion on the applications of bio-inspired algorithms for cybersecurity, this paper conducted a systematic review. We first share the cybersecurity applications using the baseline and latest variants of 12 popular bio-inspired algorithms in three categories namely ecology-based, evolutionary-based and swarm intelligence-based algorithms. A systematic review is conducted that shortlisted 371 articles. The analysis focuses on the synthesis and comparison between the research methodologies, results and limitations. In-depth discussion is made on the shortlisted and highly cited articles. The tips to select appropriate algorithm or the combination of multiple algorithms have been reported, along with the pros and cons on the design and formulations. Analysis revealed the research status where two bio-inspired algorithms namely GA and PSO dominated the research interest. The results reflected there is room for investigation in current research topic, which could start with the application of other bio-inspired algorithms to cybersecurity applications. For researchers who are experts in GA and PSO, it is believed that the knowledge extension to hybrid algorithms would share fruitful insights to the academic.

References

Ahirwar, M.K., Shukla, P.K. and Singhai, R. (2021) 'CBO-IE: a data mining approach for healthcare IoT dataset using chaotic biogeography-based optimization and information entropy', *Scientific Programming*, Vol. 2021, Article no. 8715668, pp.1–14.

Ahmed, B.K.A., Mahdi, R.D., Mohamed, T.I., Jaleel, R.A., Salih, M.A. and Zahra, M.M.A. (2022) 'A novel secure artificial bee colony with advanced encryption standard technique for biomedical signal processing', *Periodicals of Engineering and Natural Sciences*, Vol. 10, No. 1, pp.288–294.

Ahrari, A., Elsayed, S., Sarker, R., Essam, D. and Coello, C.A.C. (early access) 'Static and dynamic multimodal optimization by improved covariance matrix self-adaptation evolution strategy with repelling subpopulations', *IEEE Transactions on Evolutionary Computation*.

Ahsan, M.M., Gupta, K.D., Nag, A.K., Poudyal, S., Kouzani, A.Z. and Mahmud, M.P. (2020) 'Applications and evaluations of bio-inspired approaches in cloud security: a review', *IEEE Access*, Vol. 8, pp.180799–180814.

Ajmal, M.S., Iqbal, Z., Khan, F.Z., Ahmad, M., Ahmad, I. and Gupta, B.B. (2021) 'Hybrid ant genetic algorithm for efficient task scheduling in cloud data centers', *Computers & Electrical Engineering*, Vol. 95, Article no. 107419, pp.1–15.

Al-Gharaibeh, R.S. et al. (2021) 'Real-parameter constrained optimization using enhanced quality-based cultural algorithm with novel influence and selection schemes', *Information Sciences*, Vol. 576, pp.242–273.

Alrosan, A., Alomoush, W., Norwawi, N., Alswaitti, M. and Makhadmeh, S.N. (2021) 'An improved artificial bee colony algorithm based on mean best-guided approach for continuous optimization problems and real brain MRI images segmentation', *Neural Computing and Applications*, Vol. 33, No. 5, pp.1671–1697.

An, Y., Chen, X., Li, Y., Han, Y., Zhang, J. and Shi, H. (2021) 'An improved non-dominated sorting biogeography-based optimization algorithm for the (hybrid) multi-objective flexible job-shop scheduling problem', *Applied Soft Computing*, Vol. 99, Article no. 106869, pp.1–20.

Ang, K.M., Lim, W.H., Isa, N.A.M., Tiang, S.S. and Wong, C.H. (2020) 'A constrained multi-swarm particle swarm optimization without velocity for constrained optimization problems', *Expert Systems with Applications*, Vol. 140, Article no. 112882, pp.1–23.

Biswas, P.P., Suganthan, P.N., Qu, B.Y. and Amaratunga, G.A. (2018) 'Multiobjective economic-environmental power dispatch with stochastic wind-solar-small hydro power', *Energy*, Vol. 150, pp.1039–1057.

Carlsen, L. and Bruggemann, R. (2021) 'The 17 United Nations' Sustainable Development Goals: a status by 2020', *International Journal of Sustainable Development & World Ecology*, Vol. 29, No. 3, pp.1–11.

Çelik, E. (2020) 'A powerful variant of symbiotic organisms search algorithm for global optimization', *Engineering Applications of Artificial Intelligence*, Vol. 87, Article no. 103294, pp.1–14.

Chakraborty, S., Nama, S. and Saha, A.K. (2022) 'An improved symbiotic organisms search algorithm for higher dimensional optimization problems', *Knowledge-Based Systems*, Vol. 236, Article no. 107779, pp.1–20.

Chakraborty, S., Saha, A.K., Sharma, S., Mirjalili, S. and Chakraborty, R. (2021) 'A novel enhanced whale optimization algorithm for global optimization', *Computers & Industrial Engineering*, Vol. 153, Article no. 107086, pp.1–28.

Chatterjee, R., Mukherjee, R., Roy, P.K. and Pradhan, D.K. (2022) 'Chaotic oppositional-based whale optimization to train a feed forward neural network', *Soft Computing*, pp.1–23.

Chaudhary, P., Gupta, B.B., Chang, X., Nedjah, N. and Chui, K.T. (2021) 'Enhancing big data security through integrating XSS scanner into fog nodes for SMEs gain', *Technological Forecasting and Social Change*, Vol. 168, Article no. 120754, pp.1–11.

Chen, H., Yang, C., Heidari, A.A. and Zhao, X. (2020) 'An efficient double adaptive random spare reinforced whale optimization algorithm', *Expert Systems with Applications*, Vol. 154, Article no. 113018, pp.1–14.

Chen, X., Tianfield, H., Du, W. and Liu, G. (2016) 'Biogeography-based optimization with covariance matrix based migration', *Applied Soft Computing*, Vol. 45, pp.71–85.

Cheng, M.Y. and Prayogo, D. (2014) 'Symbiotic organisms search: a new metaheuristic optimization algorithm', *Computers & Structures*, Vol. 139, pp.98–112.

Cheng, W., Zhao, M., Xiong, N. and Chui, K.T. (2017) 'Non-convex sparse and low-rank based robust subspace segmentation for data mining', *Sensors*, Vol. 17, No. 7, Article no. 1633, pp.1–15.

Chu, S.C., Du, Z.G. and Pan, J.S. (2020) 'Symbiotic organism search algorithm with multi-group quantum-behavior communication scheme applied in wireless sensor networks', *Applied Sciences*, Vol. 10, No. 3, Article no. 930, pp.1–19.

Chui, K.T., Gupta, B.B. and Vasant, P. (2021) 'A genetic algorithm optimized RNN-LSTM model for remaining useful life prediction of turbofan engine', *Electronics*, Vol. 10, No. 3, Article no. 285, pp.1–15.

Chui, K.T., Ordóñez de Pablos, P., Shen, C.W., Lytras, M.D. and Vasant, P. (2022) 'Towards sustainable smart city via resilient internet of things', in *Resilience in a Digital Age*, pp.117–135, Springer, Cham.

Chui, K.T., Vasant, P. and Liu, R.W. (2019) 'Smart city is a safe city: information and communication technology-enhanced urban space monitoring and surveillance systems: the promise and limitations', in *Smart Cities: Issues and Challenges*, pp.111–124, Elsevier, The Netherlands.

Colorni, A., Dorigo, M. and Maniezzo, V. (1991) 'Distributed optimization by ant colonies', in *Proceedings of the First European Conference on Artificial Life*, Vol. 142, pp.134–142.

Cui, Z., Du, L., Wang, P., Cai, X. and Zhang, W. (2019) 'Malicious code detection based on CNNs and multi-objective algorithm', *Journal of Parallel and Distributed Computing*, Vol. 129, pp.50–58.

Cvitić, I., Peraković, D., Gupta, B., and Choo, K.K.R. (2022) 'Boosting-based DDoS detection in internet of things systems', *IEEE Internet of Things Journal*, Vol. 9, No. 3, pp.2109–2123.

Daneshyar, S.A. and Charkari, N.M. (2022) 'Biogeography based optimization method for robust visual object tracking', *Applied Soft Computing*, Vol. 122, Article no. 108802, pp.1–24.

Deb, K. and Jain, H. (2013) 'An evolutionary many-objective optimization algorithm using reference-point-based nondominated sorting approach, part I: solving problems with box constraints', *IEEE Transactions on Evolutionary Computation*, Vol. 18, No. 4, pp.577–601.

Deb, K., Pratap, A., Agarwal, S. and Meyarivan, T.A.M.T. (2002) 'A fast and elitist multiobjective genetic algorithm: NSGA-II', *IEEE Transactions on Evolutionary Computation*, Vol. 6, No. 2, pp.182–197.

Deng, W., Shang, S., Cai, X., Zhao, H., Zhou, Y., Chen, H. and Deng, W. (2021a) 'Quantum differential evolution with cooperative coevolution framework and hybrid mutation strategy for large scale optimization', *Knowledge-Based Systems*, Vol. 224, Article no. 107080, pp.1–14.

Deng, W., Xu, J., Song, Y. and Zhao, H. (2021b) 'Differential evolution algorithm with wavelet basis function and optimal mutation strategy for complex optimization problem', *Applied Soft Computing*, Vol. 100, Article no. 106724, pp.1–16.

Deng, W., Zhang, X., Zhou, Y., Liu, Y., Zhou, X., Chen, H. and Zhao, H. (2022) 'An enhanced fast non-dominated solution sorting genetic algorithm for multi-objective problems', *Information Sciences*, Vol. 585, pp.441–453.

Dixit, P. and Silakari, S. (2021) 'Deep learning algorithms for cybersecurity applications: a technological and status review', *Computer Science Review*, Vol. 39, Article no. 100317, pp.1–15.

European Union (2017) *Commission Staff Working Document – Digital4Development: Mainstreaming Digital Technologies and Services Into EU Development Policy*, Brussels, Belgium.

Gao, H., Sun, H., Cui, W. and Zhao, H. (2021) 'Quantum-inspired cultural fireworks algorithm for direction finding of monostatic MIMO radar', *International Journal of Wireless and Mobile Computing*, Vol. 21, No. 2, pp.182–190.

Ge, H. et al. (2020) 'Bi-space interactive cooperative coevolutionary algorithm for large scale black-box optimization', *Applied Soft Computing*, Vol. 97, Article no. 106798, pp.1–18.

Guo, Y., Lu, Y., Liu, R.W., Yang, M. and Chui, K.T. (2020) 'Low-light image enhancement with regularized illumination optimization and deep noise suppression', *IEEE Access*, Vol. 8, pp.145297–145315.

Handa, A., Sharma, A. and Shukla, S.K. (2019) 'Machine learning in cybersecurity: a review', *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery*, Vol. 9, No. 4, Article no. e1306.

Herath, T.B., Khanna, P. and Ahmed, M. (2022) 'Cybersecurity practices for social media users: a systematic literature review', *Journal of Cybersecurity and Privacy*, Vol. 2, No. 1, pp.1–18.

Hillis, W.D. (1990) 'Co-evolving parasites improve simulated evolution as an optimization procedure', *Physica D: Nonlinear Phenomena*, Vol. 42, Nos. 1–3, pp.228–234.

Hu, Y., Bie, Z., Ding, T. and Lin, Y. (2016) 'An NSGA-II based multi-objective optimization for combined gas and electricity network expansion planning', *Applied Energy*, Vol. 167, pp.280–293.

Jain, A.K. and Gupta, B.B. (2022) 'A survey of phishing attack techniques, defence mechanisms and open research challenges', *Enterprise Information Systems*, Vol. 16, No. 4, pp.527–565.

Jain, H. and Deb, K. (2013) 'An evolutionary many-objective optimization algorithm using reference-point based nondominated sorting approach, part II: handling constraints and extending to an adaptive approach', *IEEE Transactions on Evolutionary Computation*, Vol. 18, No. 4, pp.602–622.

Jiang, C. and Xue, X. (2021) 'A uniform compact genetic algorithm for matching bibliographic ontologies', *Applied Intelligence*, Vol. 51, pp.7517–7532.

John, H. (1992) 'Genetic algorithms', *Scientific American*, Vol. 267, No. 1, pp.44–50.

John, N. and Sam, S. (2021) 'Provably secure data sharing approach for personal health records in cloud storage using session password, data access key, and circular interpolation', *International Journal on Semantic Web and Information Systems*, Vol. 17, No. 4, pp.76–98.

Karaboga, D. (2005) *An Idea Based on Honey Bee Swarm for Numerical Optimization*, Technical Report-tr06, Vol. 200, pp.1–10, Computer Engineering Department, Engineering Faculty, Erciyes University.

Karami, A. and Guerrero-Zapata, M. (2015) 'A fuzzy anomaly detection system based on hybrid PSO-Kmeans algorithm in content-centric networks', *Neurocomputing*, Vol. 149, pp.1253–1269.

Kashyap, A.K., Parhi, D. and Pandey, A. (2021) 'Improved modified chaotic invasive weed optimization approach to solve multi-target assignment for humanoid robot', *Journal of Robotics and Control (JRC)*, Vol. 2, No. 3, pp.194–199.

Kaveh, A., Rahmani, P. and Eslamlou, A.D. (2021) 'An efficient hybrid approach based on Harris Hawks optimization and imperialist competitive algorithm for structural optimization', *Engineering with Computers*, Vol. 38, No. 3, pp.1–29.

Kayal, P. and Chanda, C.K. (2015) 'Optimal mix of solar and wind distributed generations considering performance improvement of electrical distribution network', *Renewable Energy*, Vol. 75, pp.173–186.

Kennedy, J. and Eberhart, R. (1995) 'Particle swarm optimization', in *Proceedings of ICNN'95 – International Conference on Neural Networks*, Vol. 4, pp.1942–1948.

Khammassi, C. and Krichen, S. (2017) 'A GA-LR wrapper approach for feature selection in network intrusion detection', *Computers & Security*, Vol. 70, pp.255–277.

Kumar, A., Das, S., Misra, R.K. and Singh, D. (2022) 'A υ-constrained matrix adaptation evolution strategy with broyden-based mutation for constrained optimization', *IEEE Transactions on Cybernetics*, Vol. 52, No. 6, pp.4784–4796.

Kusyk, J., Uyar, M.U. and Sahin, C.S. (2018) 'Survey on evolutionary computation methods for cybersecurity of mobile ad hoc networks', *Evolutionary Intelligence*, Vol. 10 No. 3, pp.95–117.

Li, F., Tan, W.J. and Cai, W. (2022a) 'A wholistic optimization of containerized workflow scheduling and deployment in the cloud-edge environment', *Simulation Modelling Practice and Theory*, Vol. 118, Article no. 102521, pp.1–16.

Li, M., Xu, G., Lai, Q. and Chen, J. (2022b) 'A chaotic strategy-based quadratic opposition-based learning adaptive variable-speed whale optimization algorithm', *Mathematics and Computers in Simulation*, Vol. 193, pp.71–99.

Li, Y., Li, X., Gao, L. and Meng, L. (2020) 'An improved artificial bee colony algorithm for distributed heterogeneous hybrid flowshop scheduling problem with sequence-dependent setup times', *Computers & Industrial Engineering*, Vol. 147, Article no. 106638, pp.1–12.

Liu, M., Yeoh, W., Jiang, F. and Choo, K.K.R. (2021a) 'Blockchain for cybersecurity: systematic literature review and classification', *Journal of Computer Information Systems*, pp.1–17.

Liu, Y., Cao, B. and Li, H. (2021b) 'Improving ant colony optimization algorithm with epsilon greedy and Levy flight', *Complex & Intelligent Systems*, Vol. 7, No. 4, pp.1711–1722.

Liu, R.W., Guo, Y., Lu, Y., Chui, K.T. and Gupta, B.B. (early access) 'Deep network-enabled haze visibility enhancement for visual IoT-driven intelligent transportation systems', *IEEE Transactions on Industrial Informatics*.

Maki, A., Sakamoto, N., Akimoto, Y., Nishikawa, H. and Umeda, N. (2020) 'Application of optimal control theory based on the evolution strategy (CMA-ES) to automatic berthing', *Journal of Marine Science and Technology*, Vol. 25, No. 1, pp.221–233.

Mao, Z. and Liu, M. (2022) 'An improved multiobjective cultural algorithm with a multistrategy knowledge base', *Applied Intelligence*, Vol. 52, pp.1157–1187.

Mehrabian, A.R. and Lucas, C. (2006) 'A novel numerical optimization algorithm inspired from weed colonization', *Ecological Informatics*, Vol. 1, No. 4, pp.355–366.

Mirjalili, S. and Lewis, A. (2016) 'The whale optimization algorithm', *Advances in Engineering Software*, Vol. 95, pp.51–67.

Mishra, P., Varadharajan, V., Tupakula, U. and Pilli, E.S. (2018) 'A detailed investigation and analysis of using machine learning techniques for intrusion detection', *IEEE Communications Surveys & Tutorials*, Vol. 21, No. 1, pp.686–728.

Nandan, V. and Rao, R. (2021) 'Low-power AES S-box design using dual-basis tower field extension method for cyber security applications', *Complex & Intelligent Systems*, pp.1–9.

Neelakandan, S., Keerthika, K., Ilanchezhian, P., Madeswaran, T., Hardas, V.B. and Sakthi, U. (2022) 'Quantum invasive weed optimization based energy aware task scheduling for cyber-physical system environment', *International Journal of Modeling, Simulation, and Scientific Computing*.

Paniri, M., Dowlatshahi, M.B. and Nezamabadi-pour, H. (2020) 'MLACO: a multi-label feature selection algorithm based on ant colony optimization', *Knowledge-Based Systems*, Vol. 192, Article no. 105285, pp.1–15.

Pant, M., Zaheer, H., Garcia-Hernandez, L. and Abraham, A. (2020) 'Differential evolution: a review of more than two decades of research', *Engineering Applications of Artificial Intelligence*, Vol. 90, Article no. 103479, pp.1–24.

Peake, J., Amos, M., Costen, N., Masala, G. and Lloyd, H. (2022) 'PACO-VMP: parallel ant colony optimization for virtual machine placement', *Future Generation Computer Systems*, Vol. 129, pp.174–186.

Price, K.V. (1996) 'Differential evolution: a fast and simple numerical optimizer', in *Proceedings of North American Fuzzy Information Processing*, pp.524–527.

Qi, L., Chen, Y., Yuan, Y., Fu, S., Zhang, X. and Xu, X. (2020) 'A QoS-aware virtual machine scheduling method for energy conservation in cloud-based cyber-physical systems', *World Wide Web*, Vol. 23, No. 2, pp.1275–1297.

Qiao, W., Yang, Z., Kang, Z. and Pan, Z. (2020) 'Short-term natural gas consumption prediction based on Volterra adaptive filter and improved whale optimization algorithm', *Engineering Applications of Artificial Intelligence*, Vol. 87, Article no. 103323, pp.1–19.

Qureshi, T.N., Javaid, N., Almogren, A., Khan, A.U., Almajed, H. and Mohiuddin, I. (2022) 'An adaptive enhanced differential evolution strategies for topology robustness in internet of things', *International Journal of Web and Grid Services*, Vol. 18, No. 1, pp.1–33.

Rauf, U. (2018) 'A taxonomy of bio-inspired cyber security approaches: existing techniques and future directions', *Arabian Journal for Science and Engineering*, Vol. 43, No. 12, pp.6693–6708.

Rechenberg, I. (1965) *Cybernetic Solution Path of an Experimental Problem*, Royal Aircraft Establishment Library Translation No. 1122.

Reynolds, R.G., Ashlock, D., Yannakakis, G.N., Togelius, J. and Preuss, M. (2011) 'Tutorials: cultural algorithms: incorporating social intelligence into virtual worlds', in *2011 IEEE Conference on Computational Intelligence and Games (CIG'11)*, pp.J–1.

Sajith, P.J. and Nagarajan, G. (2022) 'Intrusion detection system using deep belief network & particle swarm optimization', *Wireless Personal Communications*, pp.1–19.

Saleem, K., Alabduljabbar, G.M., Alrowais, N., Al-Muhtadi, J., Imran, M. and Rodrigues, J.J. (2020) 'Bio-inspired network security for 5G-enabled IoT applications', *IEEE Access*, Vol. 8, pp.229152–229160.

Sedighizadeh, D., Masehian, E., Sedighizadeh, M. and Akbaripour, H. (2021) 'GEPSO: a new generalized particle swarm optimization algorithm', *Mathematics and Computers in Simulation*, Vol. 179, pp.194–212.

Shah, P. and Kobti, Z. (2020) 'Multimodal fake news detection using a cultural algorithm with situational and normative knowledge', in *2020 IEEE Congress on Evolutionary Computation (CEC)*, pp.1–7.

Simon, D. (2008) 'Biogeography-based optimization', *IEEE Transactions on Evolutionary Computation*, Vol. 12, No. 6, pp.702–713.

Şimşir, Ş. and Taşpınar, N. (2021) 'An improved PTS scheme based on a novel discrete invasive weed optimization algorithm for PAPR reduction in the UFMC signal', *Neural Computing and Applications*, Vol. 33, No. 23, pp.16403–16424.

Storn, R. and Price, K. (1997) 'Differential evolution – a simple and efficient heuristic for global optimization over continuous spaces', *Journal of Global Optimization*, Vol. 11, No. 4, pp.341–359.

Tejani, G.G., Pholdee, N., Bureerat, S., Prayogo, D. and Gandomi, A.H. (2019) 'Structural optimization using multi-objective modified adaptive symbiotic organisms search', *Expert Systems with Applications*, Vol. 125, pp.425–441.

Tsai, H.C. (2021) 'A corrected and improved symbiotic organisms search algorithm for continuous optimization', *Expert Systems with Applications*, Vol. 177, Article no. 114981, pp.1–12.

United Nations (2015) *The 2030 Agenda for Sustainable Development*, New York, USA.

Vejdannik, M. and Sadr, A. (2022) 'Channel power optimization in WDM systems using co-evolutionary genetic algorithm', *Optical Switching and Networking*, Vol. 43, Article no. 100637, pp.1–5.

Wang, F., Zhang, H. and Zhou, A. (2021a) 'A particle swarm optimization algorithm for mixed-variable optimization problems', *Swarm and Evolutionary Computation*, Vol. 60, Article no. 100808, pp.1–12.

Wang, H., Wang, W., Zhou, X., Zhao, J., Wang, Y., Xiao, S. and Xu, M. (2021b) 'Artificial bee colony algorithm based on knowledge fusion', *Complex & Intelligent Systems*, Vol. 7, No. 3, pp.1139–1152.

Wang, R., Ma, W., Tan, M., Wu, G., Wang, L., Gong, D. and Xiong, J. (2021c) 'Preference-inspired coevolutionary algorithm with active diversity strategy for multi-objective multi-modal optimization', *Information Sciences*, Vol. 546, pp.1148–1165.

Wang, H., Wang, W., Xiao, S., Cui, Z., Xu, M. and Zhou, X. (2020) 'Improving artificial bee colony algorithm using a new neighborhood selection mechanism', *Information Sciences*, Vol. 527, pp.227–240.

Wu, Y., Wang, L. and Chen, J.F. (2021) 'A cooperative coevolution algorithm for complex hybrid seru-system scheduling optimization', *Complex & Intelligent Systems*, Vol. 7, No. 5, pp.2559–2576.

Xie, Y., Zhou, Y., Xu, J., Zhou, J., Chen, X. and Xiao, F. (2021) 'Cybersecurity protection on in-vehicle networks for distributed automotive cyber-physical systems: state-of-the-art and future challenges', *Software: Practice and Experience*, Vol. 51, No. 11, pp.2108–2127.

Xie, Y., Zhu, Y., Wang, Y., Cheng, Y., Xu, R., Sani, A.S., Yang, Y. et al. (2019) 'A novel directional and non-local-convergent particle swarm optimization based workflow scheduling in cloud-edge environment', *Future Generation Computer Systems*, Vol. 97, pp.361–378.

Yi, N., Xu, J., Yan, L. and Huang, L. (2020) 'Task optimization and scheduling of distributed cyber-physical system based on improved ant colony algorithm', *Future Generation Computer Systems*, Vol. 109, pp.134–148.

Yinka-Banjo, C. and Ugot, O.A. (2020) 'A review of generative adversarial networks and its application in cybersecurity', *Artificial Intelligence Review*, Vol. 53, No. 3, pp.1721–1736.

Zhan, Z.H., Liu, X.F., Gong, Y.J., Zhang, J., Chung, H.S.H. and Li, Y. (2015) 'Cloud computing resource scheduling and a survey of its evolutionary approaches', *ACM Computing Surveys (CSUR)*, Vol. 47, No. 4, pp.1–33.

Zhan, Z.H., Wang, Z.J., Jin, H. and Zhang, J. (2019) 'Adaptive distributed differential evolution', *IEEE Transactions on Cybernetics*, Vol. 50, No. 11, pp.4633–4647.

Zhang, K., Chen, M., Xu, X. and Yen, G.G. (2021) 'Multi-objective evolution strategy for multimodal multi-objective optimization', *Applied Soft Computing*, Vol. 101, Article no. 107004, pp.1–12.

Zhang, X., Liu, H. and Tu, L. (2020a) 'A modified particle swarm optimization for multimodal multi-objective optimization', *Engineering Applications of Artificial Intelligence*, Vol. 95, Article no. 103905, pp.1–10.

Zhang, Y., Gong, D.W., Gao, X.Z., Tian, T. and Sun, X.Y. (2020b) 'Binary differential evolution with self-learning for multi-objective feature selection', *Information Sciences*, Vol. 507, pp.67–85.

Zhao, D. et al. (2021) 'Ant colony optimization with horizontal and vertical crossover search: fundamental visions for multi-threshold image segmentation', *Expert Systems with Applications*, Vol. 167, Article no. 114122, pp.1–38.

Zhao, F., Qin, S., Zhang, Y., Ma, W., Zhang, C. and Song, H. (2019) 'A two-stage differential biogeography-based optimization algorithm and its performance analysis', *Expert Systems with Applications*, Vol. 115, pp.329–345.

Zheng, T., Liu, Y., Sun, G., Zhang, L., Liang, S., Wang, A. and Zhou, X. (2020a) 'IWORMLF: improved invasive weed optimization with random mutation and Lévy flight for beam pattern optimizations of linear and circular antenna arrays', *IEEE Access*, Vol. 8, pp.19460–19478.

Zheng, Z., Li, J. and Han, Y. (2020b) 'An improved invasive weed optimization algorithm for solving dynamic economic dispatch problems with valve-point effects', *Journal of Experimental & Theoretical Artificial Intelligence*, Vol. 32, No. 5, pp.805–829.

Zhou, Y., Zhang, W., Kang, J., Zhang, X. and Wang, X. (2021) 'A problem-specific non-dominated sorting genetic algorithm for supervised feature selection', *Information Sciences*, Vol. 547, pp.841–859.

Zou, D. and Gong, D. (2022) 'Differential evolution based on migrating variables for the combined heat and power dynamic economic dispatch', *Energy*, Vol. 238, Article no. 121664.