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Review of Research on Chemical Reaction Optimization Algorithm

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Abstract:

As an intelligent optimization algorithm, the chemical reaction optimization algorithm has many advantages of strong robustness, flexible design, and easy implementation. Therefore, it is widely used to solve optimization problems in kinds of different fields. Aiming at the vacancy of the chemical reaction optimization algorithm in the research review, based on the introduction of the basic principles of chemical reaction optimization algorithm, this article briefly describes the theoretical research and parameter settings of chemical reaction optimization algorithm. And from the perspective of improvement and application, several improved methods and applications of chemical reaction optimization algorithm in recent years are reviewed. Firstly, the article introduces the application of algorithm in some fields. Then the improved advantages, disadvantages and applicable scenarios of the algorithm in terms of design framework, molecular structure and operation operators are analyzed and summarized. At the same time, the advantages, disadvantages and applicable scenarios of the hybrid algorithms which combine the chemical reaction optimization algorithm with other algorithms are also analyzed and summarized. Finally, the current situation and future development of chemical reaction optimization algorithm are summarized and prospected, which would provide inspiration and reference for other follow-up researches.

Keywords*: Chemical reaction optimization algorithm, Swarm intelligence, Review, Algorithm improvement, Hybrid algorithm.*

I. INTRODUCTION

Chemical Reaction Optimization Algorithm (CROA) [1] is an intelligent optimization algorithm proposed by LAM et al. in 2010. Inspired by the nature of chemical reactions, it seeks the optimal solution by imitating the changes in the movement of molecules during chemical reactions.

The chemical reaction optimization algorithm has the advantages of strong robustness, flexibility of algorithm design and simplicity of software implementation. Since it was proposed, it has attracted much attention from academia and has been widely used in various fields, such as: combinatorial optimization, control and identification, resource management, communication network and so on. In addition, articles on the application, improvement and algorithm fusion of chemical reaction optimization algorithm are also

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emerging in an endless stream. However, there are few domestic and foreign articles on the research review of chemical reaction optimization algorithm. Therefore, this paper first briefly introduces the principle of the chemical reaction optimization algorithm and the basic molecular operations of the four elementary reactions, and summarizes the theoretical basis and parameter setting research of the chemical reaction optimization algorithm. Then, a comprehensive research review of chemical reaction optimization algorithm is carried out from the perspective of improvement and application. It provides convenience for other scholars to understand the progress and achievements of CROA, and also provides inspiration for the continued research and improvement of CROA. It is expected that this algorithm can be used to solve more practical problems.

II. CHEMICAL REACTION OPTIMIZATION ALGORITHM

2.1 Principle of Chemical Reaction Optimization Algorithm

Chemical reaction optimization algorithm is inspired by the nature of chemical reactions. The chemical reaction is a natural process by which a substance changes from an unstable state to a stable state. From a microscopic point of view, a chemical reaction starts with some unstable molecules with excess energy, and the molecules interact through a series of elementary reactions and transform into stable molecules with the lowest energy. The chemical reaction optimization algorithm simulates this molecular motion and change process in the chemical reaction. The process of optimizing the objective function is regarded as a chemical reaction process in an airtight container, and four primary reactions are adopted: collision, decomposition, exchange and synthesis. Different molecular structure (ω) represents different solution to the problem. Molecules are the main body of the algorithm to perform operations. Each molecule contains two kinds of energy, kinetic energy (KE) and potential energy (PE), following the law of energy conservation. The kinetic energy reflects the ability of the molecule to undergo basic reactions, and the potential energy represents the objective function value corresponding to the current molecule. Therefore, the optimal solution of the objective function obtained by the chemical reaction optimization algorithm is the molecule with the lowest potential energy in the primary reaction.

2.2 Basic Molecular Operations

(1) collision reaction

Only one molecule is involved in the collision reaction, and the slight collision with the container wall produces a new molecule with little change in structure and energy. Assuming that the original molecular structure is ω and the new molecular structure generated is ω', the conditional formula for the collision reaction to occur is:

$$PE_{\omega} + KE_{\omega} \geq PE_{\omega'} \tag{1}$$

where $PE_{\omega'}$ is the potential energy of the newly generated molecule. In the collision reaction, the original molecule will lose a certain kinetic energy value for each collision, and the lost kinetic energy

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value will be stored in the energy buffer area of the container. Let a system parameter $KElossRate$ be the maximum percentage of kinetic energy loss, so $q \in [0, KElossRate]$, the ratio of kinetic energy loss is q. According to the law of conservation of energy, the new molecular kinetic energy can be obtained as:

$$KE_{\omega'} = \left(PE_{\omega} + KE_{\omega} - PE_{\omega'}\right) \times (1-q) \tag{2}$$

After the collision reaction is over, update the cached energy $buffer$ in the energy buffer area to:

$$buffer = buffer + \left(PE_{\omega} + KE_{\omega} - PE_{\omega'}\right) \times q \tag{3}$$

(2) decomposition reaction

Only one molecule is involved in the decomposition reaction, but it collides violently with the walls of the container, producing two new molecules. The molecular structure of the new molecule is quite different from that of the original molecule, and the energy changes are also large. Assuming that the original molecular structure is c, and the new molecular structures generated are ω_1' and ω_2', respectively, the conditional formula for the decomposition reaction to occur is:

$$PE_{\omega} + KE_{\omega} \geq PE_{\omega_1'} + PE_{\omega_2'} \tag{4}$$

where $PE_{\omega_1'}$ and $PE_{\omega_2'}$ are the potential energies of the two newly generated molecules, respectively. Let k be a random number in the range of 0 to 1. According to the law of conservation of energy, the kinetic energy of the two new molecules can be obtained as:

$$KE_{\omega_1'} = \left(PE_{\omega} + KE_{\omega} - PE_{\omega_1'} - PE_{\omega_2'}\right) \times k \tag{5}$$

$$KE_{\omega_2'} = \left(PE_{\omega} + KE_{\omega} - PE_{\omega_1'} - PE_{\omega_2'}\right) \times (1-k) \tag{6}$$

According to formula (4), it can be concluded that the equation is established only when KE_{ω} is large. However, the reality is that this equation is difficult to satisfy all the time. Therefore, in order to ensure that the decomposition reaction can occur normally, it is necessary to supplement it with the cached energy stored in the energy buffer in the previous collision reaction to increase the probability of the decomposition reaction. So, when formula (4) is difficult to satisfy, the decomposition reaction can still be realized if the following conditional formula is satisfied:

$$PE_{\omega} + KE_{\omega} + buffer \geq PE_{\omega_1'} + PE_{\omega_2'} \tag{7}$$

In addition, in order to prevent the value of the cached energy $buffer$ from accumulating too much and affecting the kinetic energy value of the new molecule, the kinetic energy value of the new molecule becomes very large, which in turn affects the subsequent primary reactions. Therefore, four independent

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random numbers between 0 and 1 of a_1, a_2, a_3 and a_4 are introduced to limit the kinetic energy value of the new molecule. At this time, according to the law of conservation of energy, the kinetic energy expressions of the two new molecules become:

$$KE_{\omega_1'} = \left(PE_{\omega} + KE_{\omega} + buffer - PE_{\omega_1'} - PE_{\omega_2'}\right) \times a_1 \times a_2 \tag{8}$$

$$KE_{\omega_2'} = \left(PE_{\omega} + KE_{\omega} + buffer - PE_{\omega_1'} - PE_{\omega_2'} - KE_{\omega_1'}\right) \times a_3 \times a_4 \tag{9}$$

After the decomposition reaction is over, update the cache energy $buffer$ in the energy buffer area to:

$$buffer = buffer + PE_{\omega} + KE_{\omega} - PE_{\omega_1'} - PE_{\omega_2'} - KE_{\omega_1'} - KE_{\omega_2'} \tag{10}$$

(3) exchange reaction

There are two molecules involved in the exchange reaction, and there is a slight collision between the molecules to generate two new molecules. The molecular structure of the new molecule is similar to that of the original molecule, and a small amount of energy is exchanged between the molecules. Assuming that the original molecular structures are ω_1 and ω_2, respectively, and the new molecular structures generated are ω_1' and ω_2', respectively, the conditional formula for the exchange reaction to occur is:

$$PE_{\omega_1} + PE_{\omega_2} + KE_{\omega_1} + KE_{\omega_2} \geq PE_{\omega_1'} + PE_{\omega_2'} \tag{11}$$

where $PE_{\omega_1'}$ and $PE_{\omega_2'}$ are the potential energies of the two newly generated molecules, respectively. Let p be a random number in the range of 0 to 1. According to the law of conservation of energy, the kinetic energy of the two new molecules can be obtained as:

$$KE_{\omega_1'} = \left(PE_{\omega_1} + PE_{\omega_2} + KE_{\omega_1} + KE_{\omega_2} - PE_{\omega_1'} - PE_{\omega_2'}\right) \times p \tag{12}$$

$$KE_{\omega_2'} = \left(PE_{\omega_1} + PE_{\omega_2} + KE_{\omega_1} + KE_{\omega_2} - PE_{\omega_1'} - PE_{\omega_2'}\right) \times (1 - p) \tag{13}$$

After the exchange reaction is over, because the overall energy loss is negligible, the value of the cached energy wxx1 in the energy buffer area remains unchanged.

(4) synthesis reaction

There are two molecules involved in the synthesis reaction, but the collision between the molecules is violent, and a new molecule is generated. The resulting new molecular structure has a huge gap with the original molecular structure, and the energy changes greatly. Assuming that the original molecular structures are ω_1 and ω_2 respectively, and the resulting new molecular structure is ω', the conditional formula for the synthesis reaction to occur is:

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$$PE_{\omega_1} + PE_{\omega_2} + KE_{\omega_1} + KE_{\omega_2} \geq PE_{\omega'} \tag{14}$$

where $PE_{\omega'}$ is the potential energy of the newly generated molecule. According to the law of conservation of energy, the kinetic energy of the new molecule is expressed as:

$$KE_{\omega'} = PE_{\omega_1} + PE_{\omega_2} + KE_{\omega_1} + KE_{\omega_2} - PE_{\omega'} \tag{15}$$

2.3 Chemical Reaction Optimization Algorithm Features

(1) The chemical reaction optimization algorithm is a design framework that allows different operators to be deployed to solve different problems.

(2) The superiority of the chemical reaction optimization algorithm depends on the transformation and transfer of energy in different entities and different forms while following the law of energy conservation.

(3) The characteristics of other properties that can be incorporated into the molecular structure make the design of different operators more flexible, and also make the CROA algorithm more flexible.

(4) According to the characteristics of the four primary reactions in the chemical reaction optimization algorithm, the collision force of the collision and the exchange reaction is slight, and the new molecular structure and energy generated do not change much, which are suitable for searching for local optimal solutions; the collision force of the decomposition and the synthesis reaction is intense, and the new molecular structure and energy generated vary greatly, which are suitable for jumping out of the local search for the global optimal solution. Therefore, the chemical reaction optimization algorithm has the characteristics of fast convergence speed and strong robustness, and can effectively avoid falling into local optimum.

(5) Compared with other intelligent optimization algorithms, the chemical reaction optimization algorithm has less setting parameters, simple algorithm and easy implementation. At the same time, the parallelization of the chemical reaction optimization algorithm is also easy to implement and modify because of the variability of the population and the fact that no synchronization between computational units is required.

(6) During the operation of the chemical reaction optimization algorithm, the feedback information is not used enough, which makes it easy to fall into redundant iterations in the solution process, especially in the later stage of the solution, resulting in a greatly reduced solution rate.

III. THEORETICAL RESEARCH ON CHEMICAL REACTION OPTIMIZATION ALGORITHM

In terms of theoretical research on chemical optimization algorithms, Jin et al. [2] realized two solution representations based on permutation and vector, and proved that the vector-based representation is better than the permutation-based representation in the grid scheduling problem of independent tasks. Lam et al. [3] proposed a real-coded version of the chemical reaction optimization algorithm in 2012: real-coded chemical reaction optimization (RCCRO), which makes the algorithm suitable for solving continuous optimization problems after simple adjustments. This not only broadens the scope of application of the

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algorithm to a certain extent, but also provides a possibility for mathematical verification of the algorithm performance in the later stage. At the same time, in order to reduce the influence of the perturbation function on the chemical reaction optimization algorithm for solving continuous problems, Yu et al. [4] studied the performance of the chemical reaction optimization algorithm for solving different continuous problems under different perturbation functions. This also provides prior knowledge and inspiration for designing chemical reaction optimization algorithms for different optimization problems later. Stegherr et al. [5] implemented a parallelized variant of the chemical reaction optimization algorithm to reduce convergence time and scalability by exploiting a multi-core computing architecture.

Lam et al. [6] proved the global convergence of the algorithm from the perspective of mathematical formula derivation by modeling the chemical reaction optimization algorithm as a finite absorption Markov chain on the basis of the real number coded version of the chemical reaction optimization algorithm. And the necessary conditions for the algorithm to converge to the global optimal solution, the convergence speed and the expected time to reach the first optimal solution are analyzed theoretically. This provides the necessary theoretical basis for studying the utility of chemical reaction optimization algorithm.

IV. CHEMICAL REACTION OPTIMIZATION ALGORITHM PARAMETER SETTIINGS

The parameters of the chemical reaction optimization algorithm mainly include the initial number of molecules ($PopSize$), the determination factor of collision type ($MoleColl$), the maximum percentage of kinetic energy loss ($KElossRate$), the initial value of kinetic energy ($InitialKE$), the judgment factor of collision and decomposition reaction (α), and the judgment factor of exchange and synthesis reactions (β). Where $MoleColl$ is used to select the reaction type of monomolecular or bimolecular, and determines the number of molecules in which the primary reaction occurs; the judgment factors α and β are used to control the probability of decomposition and synthesis reactions, and determine the ability of the algorithm to jump out of the local optimum. Reference [7] gives suggested values for these parameters: $PopSize=10$; $MoleColl=0.2$; $KElossRate=0.2$; $InitialKE=1000$; $\alpha=500$; $\beta=10$. However, when solving practical problems, in order to maximize the optimization performance of the chemical reaction optimization algorithm on a specific problem, some parameter tuning needs to be performed to determine the best combination of parameter values. For example, literature [8] proposed to use a dynamic change strategy to control the values of key parameters α and β to improve the efficiency of problem solving and balance the relationship between local optimization and global optimization. Reference [9] analyzed the influence of different parameter values on the performance of the algorithm through the method of experimental design. It was concluded that the three parameters $InitialKE$, $KElossRate$ and β jointly determine the convergence speed of the algorithm and the ability to jump out of the local optimum. All of these provide guidance for the parameter setting of chemical reaction optimization algorithm in solving other practical problems, and also provide reference for the study of parameter combination setting and self-adaptive parameter study in the later stage.

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In order to reduce the workload of parameter adjustment in the chemical reaction optimization algorithm, the literature [10] simplified the parameters of the standard chemical reaction optimization algorithm into three categories: energy-related, reaction-related, and real-number coding-related. And an adaptive scheme is proposed to automatically adjust the corresponding parameter values, so that the algorithm can be better adapted to different practical problems.

V. RELATED APPPLICATION OF CHEMICAL REACTION OPTIMIZATION ALGORITHM

The flexibility and ease of implementation of the algorithmic framework design enable chemical reaction optimization algorithms to be widely applicable to different practical problems, while having the potential to solve problems that have not been successfully solved by other algorithms.

5.1 Application of CROA in Combinatorial Optimization Field

Reference [11] applied the chemical reaction optimization algorithm to solve the classical traveling salesman problem (TSP). The algorithm framework and four elementary reactions of the chemical reaction optimization algorithm were designed in a discrete problem environment, and the effectiveness of the algorithm was verified by the experimental simulation of the TSP data set.

Reference [12] applied chemical reaction optimization algorithm to optimize discrete network reconfiguration (NR) problems to improve the performance and reliability of modern power distribution systems.

5.2 Application of CROA in Control and Identification Field

Reference [13] applied the chemical reaction optimization algorithm to solve the population transfer problem that it proposed based on the Markov open queue network model. The population transition probability matrix was manipulated to maximize the probability of general streaming. The simulation results showed that the chemical reaction optimization algorithm had better performance than other control population transfer strategies.

According to the characteristics of chemical reaction optimization algorithm with strong global optimization ability, literature [14] combined the mixed sensitivity method in H_∞ control theory, and proposed a H_∞-PID controller design method based on chemical reaction optimization algorithm. It could take into account the excellent performance of PID controller and H_∞ controller.

Reference [15] applied the chemical reaction optimization algorithm to solve the problem of handwritten character recognition in Bengali. The recognition accuracy of the model was improved by designing the algorithm to search for sub-images with the most obvious features.

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5.3 Application of CROA in Resource Management Field

Reference [16] applied the chemical reaction optimization algorithm to optimize the scheduling problem of robotic manufacturing cells. Molecules were selected for primary reaction by linear sorting selection based on the number of iterations, and then local search was performed after the primary reaction was completed, which improved the convergence speed of the algorithm and avoided the algorithm from falling into local optimum.

Reference [17] applied the chemical reaction optimization algorithm to solve the wind-based economic emission scheduling problem. The concept of quasi-opposition based learning was introduced, and the algorithm convergence speed was accelerated by initializing the quasi-backward seed cluster and generating the quasi-backward population by using the hopping rate.

Reference [18] proposed a micro-cloud selection strategy based on the chemical reaction optimization algorithm for the dual-objective micro-cloud selection optimization problem in the mobile cloud environment. It reduced the energy consumption of mobile devices while improving application performance in mobile cloud environments. However, there was still a certain gap between the experimental simulation environment of this study and the real environment, and it was necessary to consider adding enough variable factors to make the results close to the real situation.

Reference [19] proposed a fog computing in-vehicle network architecture based on non-orthogonal multiple access for the resource management problem in the internet of vehicles. The resource management problem was decomposed into two sub-problems: sub-channel and power allocation. Then the chemical reaction optimization algorithm and the chemical reaction optimization algorithm of the real number coding version were used to solve these two sub-problems respectively, which improved the energy efficiency of the system.

5.4 Application of CROA in Communication Network Field

According to the advantages of fast convergence speed and flexible design of chemical reaction optimization algorithm, literature [20] proposed an evolutionary algorithm based on chemical reaction optimization algorithm to solve the network coding optimization problem. The number of coding links in the network was minimized at a given target transmission rate.

Reference [21] designed multiple operators under the framework of chemical reaction optimization algorithm, so that chemical reaction optimization algorithm could generate feasible solutions that satisfied the constraints of cognitive radio spectrum allocation problem. The effectiveness and superiority of the algorithm were proved by simulation experiments.

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VI. IMPROVEMENT AND APPLICATION OF CHEMICAL REACTION OPTIMIZATION ALGORITHM

The chemical reaction optimization algorithm is a design framework in which other properties can be incorporated into the molecular structure. Therefore, when solving practical problems, it is often possible to design, combine, and improve chemical reaction optimization algorithm according to the specific nature of the problem, so as to find the best algorithm that can solve specific problems. The following mainly introduces the improvement and application of chemical reaction optimization algorithm in some practical problems in recent years from the aspects of design framework, molecular structure, operation operators and other improvements, as shown in TABLE I.

TABLE I. Summary of advantages, disadvantages and applications of improved chemical reaction optimization algorithm

Improvement type	Name	Improvement mechanism	Advantage	Disadvantage	Application Scenario
Design Framework	CRO_V2 [2]	Divide the iteration phase into two parts. In the first part, only the collision reaction and the decomposition reaction are allowed to occur. After reaching a predefined number of iterations, the second part begins, which is similar to the entire iterative phase of the specification framework, but excludes decomposition reaction.	Ability to solve large-scale problems.	Compared with the particle swarm optimization algorithm, the convergence speed of the improved algorithm is still slower.	Task scheduling problems in grid computing.
	VNS-CRO [22]	Combined with the constrained critical path rearrangement strategy, a variable neighborhood search method with balanced neighborhood structure is designed.	It can take into account the global scheduling perspective while ensuring the fixed timing of the construction plan.	Extend planning time when resources are insufficient.	Task scheduling and subcontracting optimization of road construction schedule planning under heterogeneous resource environment.
Molecular Structure	DMSCRO [23]	Bimolecular structure: one is used to encode the execution order of tasks in the DAG job, and the other is used to encode the mapping of tasks to	Optimization speed and capabilities have been improved.	The space complexity is high.	Directed acyclic graph task scheduling problem.

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		compute nodes.			
	O MOCRO [24]	Multi-objective optimization problems are handled using a Pareto sorting scheme, and an orthogonal experimental design with quantitative techniques is used to generate dispersed initial population molecules in the initial stage.	The performance is better than the comparison algorithm MOPSO.	Compared with NSGA-II, the improvement effect is not significant.	The multi-objective optimal design problems for brushless DC motors.
	ICROA [25]	The velocity and position update formulas of particle swarms are introduced into the disturbance function of the molecular structure update expression to improve.	Compared with CROA, it converges quickly and does not get stuck in local optimum.	Compared with the particle swarm optimization algorithm, the improvement effect is not significant.	Economic evaluation problem of power smoothing in wind-hydrogen-fuel grid-connected systems.
	ICRO [26]	The velocity and position update formulas of particle swarms are introduced into the perturbation function of the molecular structure update expression for improvement, and the elite retention strategy is introduced in the iterative process.	It has better optimization effect and faster convergence speed than CRO.	Lack of comparative arguments with other types of algorithms.	Design optimization of high-speed brushless DC motor.
Operation Operator	MOECRO/D [27]	Polynomial mutation and multi-molecular collision operators are introduced in exchange reaction and synthetic reaction.	A non-dominated solution set with good convergence and diversity can be obtained.	The degree of convergence on discontinuous benchmark functions is not good enough.	20 benchmark functions.
	VNCRO [28]	The collision reaction is designed and realized by the experience learning domain structure and the variable-step domain search; the exchange reaction is designed and realized by the priority process cross-operation.	The advantages of solving large-scale examples are obvious.	The algorithm complexity is increased.	The reentrant scheduling problem with uncertain processing time.
	Hybrid Artificial Chemic	The correction operator for greedy strategies is introduced in the Artificial Chemical Reaction Optimization Algorithm (ACROA) [30].	The global search ability and convergence ability are	It will consume more CPU time in some cases.	0-1 knapsack problem.

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	al Reaction Optimization Algorithm [29]		obviously better than the comparison algorithms.		
	IMCRO [31]	The new cyclic shift operator and the new two-step crossover operator are added to the decomposition reaction and the exchange reaction, respectively.	It performs better than other heuristics on random and real sequences.	Compared with CRO_SCS, IMCRO does not significantly reduce the average length of the shortest common super-sequence.	The shortest common super-sequence problem.
Other Improvements	NCRO [32]	The new fast non-dominated sorting method with quasi-linear average time complexity is introduced into the multi-objective chemical reaction optimization algorithm.	The optimal solution diversity can be maintained on the Pareto optimal front, and it can converge to the Pareto optimal front.	It cannot solve problems with curvilinear fronts.	Multi-objective optimization problem.
	PCRO [33]	A new coding mechanism is designed, the adaptive neighborhood structure selection mechanism is embedded, the grid-based crowding distance strategy is introduced, and the kinetic energy-based search procedure is developed.	The improvement effect is better than the comparative algorithms in the three comparison indexes.	The computational complexity of the algorithm is increased.	Multi-regional environmental/economic scheduling optimization problem.
	FMIFS-RCCRO-FCM [34]	The chemical reaction optimization algorithm is used for optimal cluster center generation for fuzzy clustering.	It is better than other methods in terms of efficiency and accuracy.	The training time of the algorithm is prolonged.	Analysis and modeling of intrusion detection systems.

VII. FUSION OF CHEMICAL REACTION ALGORITHM WITH OTHER ALGORITHMS

The four elementary reactions in the chemical reaction optimization algorithm can well balance the local search ability and global search ability of the algorithm, and effectively avoid the algorithm from falling into local optimum. This makes the algorithm have the conditions and advantages to integrate with

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other intelligent optimization algorithms. The improvements and applications of the chemical reaction optimization algorithm integrated with some other intelligent optimization algorithms are summarized below, as shown in TABLE II.

TABLE II. Summary of advantages, disadvantages and applications of hybrid chemical reaction optimization algorithm

Intelligent Algorithm	**Name**	**Fusion Mechanism**	**Advantage**	**Disadvantage**	**Application Scenario**
Ant Colony Optimization (ACO)	CRACA [35]	In the early stage of ACO, CROA is used to generate the initial feasible solution, and the feasible solution is transformed into the initial pheromone of ACO through the pheromone transformation strategy.	It has good convergence performance, high computational efficiency and good generalization ability.	The computational complexity of the algorithm is increased.	Traveling salesman problem.
Particle Swarm Optimization (PSO)	ACRO-PSO [36]	Introduce *PBest* and *GBest* to improve neighborhood operators, modify decomposition and synthesis criteria, and add an end operator in the last iteration.	Convergence accuracy and convergence speed have been improved.	The best results are not obtained for all functions.	7 benchmark functions.
	HBCRO-BPSO [37]	The PSO equation is used as a neighborhood operator for collision reaction and exchange reaction.	Improve classifier performance while reducing the number of required features.	The applicability of the algorithm on ultra-high-dimensional datasets with a large number of samples is not validated.	11 benchmark datasets.
Higher order neural	CRO-HONN [38]	Apply CROA to the weight set training of PSNN.	It has high classificati	The applicability of the	8 benchmark datasets.

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network			on accuracy and low error rate.	algorithm in practical engineering problems is not verified.	
	HONN training algorithm based on chemical reaction optimization [39]	CROA is improved by introducing a greedy process to update reactant molecules, which is then applied to the training process of PSNN.	The classification accuracy of the algorithm has been improved.	The improvement in classification accuracy is not significant for datasets with smaller training sets.	Realization of ILI-MIL method; multiple example test Musk dataset; image recognition dataset.
Sequential Insertion Algorithms (SI)	ICROA [40]	Generate the initial feasible solution of CROA with SI.	High accuracy.	When the number of workpieces is large, ICROA runs longer than the comparison algorithm.	Multi-type workpiece processing robot manufacturing cell scheduling problem.
Tabu search algorithm (TS)	CROTS [41]	Introduce elite retention mechanism and tabu search.	The current optimal solution for the case can be obtained.	The improvement effect is not significantly better than the comparison algorithm.	Flexible job shop scheduling problem.
Greedy Algorithm	GCRO [42]	In the initial stage of CROA, the greedy algorithm is introduced to generate good initial molecular population.	The quality of the solution is improved.	The algorithm runs longer.	Traveling salesman problem.
Water Wave Optimization Algorithm (WWO)	WCRO [43]	CROA only retains the collision reaction and exchange reaction to optimize the individual population, and WWO reconstructs the propagation	The optimization performance is better.	The overall complexity of the algorithm increases.	Displacement flow shop scheduling problem.

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		operation, the refraction operation, and the breaking wave operation to optimize the overall population.			
Artificial Bee Colony Algorithms (ABC)	AB-CRO [44]	Use ABC to generate the position of the initial population, and then use CROA to update the current position of the population in the search space.	Higher solution accuracy can be achieved.	Convergence is slower than the ABC algorithm.	Identification and classification of optimal feature subsets; medical diagnosis

VIII. BRIEF REVIEW

As a new meta-heuristic intelligent optimization algorithm, chemical reaction optimization algorithm has attracted much attention since it was proposed, and has gradually become an important research topic. The transformation and transfer of energy in different entities and forms make chemical reaction optimization algorithm unique among intelligent algorithms. The canonical version and the real-encoded version of the algorithm make the algorithm capable of solving both discrete and continuous problems. The flexibility and ease of implementation of the algorithm design enable the chemical reaction optimization algorithm to be well integrated with other algorithms, while also having the potential to solve those problems that have not been solved by other intelligent algorithms. Through continuous research and development, the chemical reaction optimization algorithm has been widely used in various fields, and its improvement and application research for different practical problems is also deepening.

Compared with other classical intelligent optimization algorithms, the research time of chemical reaction optimization algorithm is still short. Although various improvement strategies and algorithm fusion have improved the solution performance of the algorithm to a certain extent, there are still areas that need to be improved and long-term concentrated research is required. (1) Theoretical research on CROA. The theoretical research of the algorithm is still on the proof of global convergence, and the theoretical research on other aspects of stability, complexity and the main factors affecting the performance also needs to be further promoted. In addition, the parameter settings of the algorithm often have a great impact on the overall performance of the algorithm. At present, the parameter selection of CROA is still based on experience or experimental design, and depends on specific problems. Therefore, it is also necessary to study the specific setting of parameters theoretically, and analyze whether it has the universal parameter combination that does not require precise adjustment. (2) Research on CROA application. Chemical reaction optimization algorithm has been widely used in various fields, and improved applications for specific problems have emerged in an endless stream, but there are still defects. There is still a lot of research space on how to make the theoretical problems solved as close to reality as possible and obtain the optimal solution. At present, CROA is mostly used to solve single-objective optimization problems,

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and there are few applied researches on multi-objective, multi-dimensional, dynamic uncertainty, etc., which need to be further promoted. (3) Research on CROA improvement. The characteristics of the four primary reactions in the chemical reaction optimization algorithm make the algorithm have good global convergence. Among them, decomposition reaction and synthesis reaction operations can be widely considered to be combined with other algorithms that are easy to fall into local optimum, so as to help other algorithms improve population diversity and jump out of local optimum. However, there are few improvement studies on the insufficient utilization of feedback information in the solution process of CROA. It is also worth considering how to avoid the algorithm from easily falling into redundant iterations during the solution process, especially in the later stage of the solution, and to improve the efficiency of the solution.

IX. CONCLUSION

The characteristics and advantages of the chemical reaction optimization algorithm make it have a very broad application research prospect. How to improve it to meet the specific practical problems is the research focus. On the basis of explaining the principle of chemical reaction optimization algorithm and related theories, this paper introduces the application and research of the algorithm in different fields in recent years. The improvement and application of chemical reaction optimization algorithm are reviewed from the aspects of algorithm design framework, molecular structure, operation operator and algorithm fusion. Finally, the algorithm is summarized and the prospect of future development is made to provide guidance and reference for the follow-up research.

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