**RIME optimization algorithm**

Rime-ice is resulted from accumulated water vapor in the air that has not yet condensed. It freezes and sticks to objects such as tree branches at low temperatures. Due to their unique climatic characteristics and topography, some regions form a unique landscape like rime-ice every year, as shown in Figure 1.

|  |  |  |  |
| --- | --- | --- | --- |
|  | |  | |
| (a) soft rime | (b) hard rime | |
| **Figure 1.** Rime-ice real scene[[1]](#footnote-1) | | |

The growth process of rime ice is determined by the temperature, wind speed, humidity, air, and other factors, and rime formation varies under different conditions. At the same time, due to the influence of environmental factors and the growth pattern, rime-ice cannot grow indefinitely, and it will stop growing when it reaches a relatively stable state. The growth pattern of rime is generally divided into two types: soft-rime and hard-rime, which is mainly determined by the wind speed during the formation process, as shown in Figure 2, where ΔABC represents the growth plane of rime, and D1, D2, D3, D4 represent the birth points of rime. Usually, soft rime is generated in a breeze environment, and hard rime is formed in a high-wind environment. The breeze is characterized by small wind speed and variable wind direction, and the wind exists in all directions simultaneously and in the same height plane, as shown in Figure 2(a). Therefore, the soft rime formed by the breeze grows slowly and randomly. On the other hand, a gale is characterized by high wind speed and roughly the same wind direction in the same height plane, as shown in Fig. 2(b). Therefore, the hard rime formed by the gale is fast and grows in approximately the same direction.



|  |  |
| --- | --- |
| (a) soft-rime | (b) hard-rime |

**Figure 2.** The formation process of soft rime and hard rime under different environments

In summary, this study is inspired by the growth mechanism of rime-ice and proposes a soft-rime search strategy for algorithm search by simulating the motion of soft-rime particles. Also, a hard-rime puncture mechanism is proposed to exploit the algorithm by simulating the crossover behavior between hard rime agents. Finally, the selection mechanism of the metaheuristic algorithm is improved, and the positive greedy selection mechanism is proposed. This paper proposes the RIME algorithm with better performance by combining the above three mechanisms.

# 3 Mathematical model of the RIME

In this section, the growth process of each rime strip is simulated by analyzing the effects of wind speed, freezing coefficient, the cross-sectional area of the attached material, and growth time. On the other hand, inspired by the diffusion-limited aggregation [50] method of simulating metal particle aggregation, the motion process of each rime particle coalescing into a rime agent is simulated by modeling the motion behavior of each rime particle, and the final generated rime-agent is in the form of a strip crystal. The RIME consists of four stages: the initialization of rime clusters, the proposed soft-rime search strategy, the proposed hard-rime puncture mechanism, and the improvement of the greedy selection mechanism.

## 3.1 Rime cluster initialization

Inspired by reality, this paper treats each agent rime as the searched agent of the algorithm and the rime-population formed by all agents as the population of the algorithm. Firstly, the whole rime-population is initialized. The rime population consists of  rime agents and each rime- agent consists of rime-particles , as shown in Figure 3 and Eq. (1). Thus, the rime-population can be directly represented by the rime-particles , as shown in Eq. (2).

|  |  |
| --- | --- |
|  | (1) |
|  | (2) |

where is the ordinal number of the rime agent and is the ordinal number of the rime particle. In addition, is used to denote the growth state of each rime-agent, i.e., the fitness value of the agent in the meta-heuristic algorithm.



**Figure 3.** Initialization of the rime space

## 3.2 Soft-rime search strategy

In a breezy environment, soft-rime growth is strongly random, and the rime particles can freely cover most of the surface of the attached object but grow slowly in the same direction. Inspired by the growth of soft-rime, this study proposes a soft-rime search strategy using the strong randomness and coverage of rime particles, which enables the algorithm to cover the entire search space in the early iteration quickly and does not easily fall into the local optimum.

When the rime particles condense into soft-rime agents, there are the following characteristics:

1) Before the particles condense to form a soft rime agent, each particle will wander according to a certain law, and the efficiency of the wandering is affected by environmental factors.

2) If the free-state rime particles move to the vicinity of a soft-rime agent, they will condense with the particles in the agent so that the stability of the soft-rime agent will change.

3) The distance between the centers of the two particles adhering to each other is not fixed, as the degree of condensation varies between each particle.

4) If the particles move directly outside the escape radius, no interparticle condensation occurs.

5) During the formation of a soft rime, the random condensation of each particle increases the area to which the agent is attached, resulting in a greater probability of free particle condensation. However, the agent will not grow indefinitely and will eventually reach a stable state due to environmental factors.

In this paper, corresponding to the five motion characteristics of the rime particles, the process of condensation of each particle is concisely simulated, as shown in Figure 4, and the position of the rime- particles is calculated as shown in Eq. (3).

|  |  |
| --- | --- |
| *,* | (3) |

where, is the new position of the updated particle, and and denote the -th particle of the -th rime-agent. is the -th particle of the best rime-agent in the rime-population . The parameter is a random number in the range (-1,1) and controls the direction of particle movement together with will change following the number of iterations, as shown in Eq. (4). is the environmental factor, which follows the number of iterations to simulate the influence of the external environment and is used to ensure the convergence of the algorithm, as shown in Eq. (5). is the degree of adhesion, which is a random number in the range (0,1), and is used to control the distance between the centers of two rime-particles.

|  |  |
| --- | --- |
|  | (4) |

where is the current number of iterations and is the maximum number of iterations of the algorithm.

|  |  |
| --- | --- |
|  | (5) |

where the mathematical model of is the step function, denotes rounding; the default value of is 5, which is used to control the number of segments of the step function. Returning to Eq. (3), and are the upper and lower bounds of the escape space, respectively, which limit the effective region of particle motion. is the coefficient of being attached, which affects the condensation probability of an agent and increases with the number of iterations, as shown in Eq. (6).

|  |  |
| --- | --- |
|  | (6) |

is a random number in the range ([51]) which, together with , controls whether the particles condense, i.e., whether the particle positions are updated. The pseudo-code for the soft-rime search strategy is shown in Algorithm 1.

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| **Algorithm 1** Pseudo-code of the soft-rime search strategy |
| Initialize the rime-population  Get the current optimal agent and optimal fitness  **While** Coefficient of adherence  **For**  **For**  **If**  Position update according to the characteristics of the rime particles by Eq. (3)  **End If**  **End For**  **End For**  Update the current optimal agent and optimal fitness    **End While** |



**Figure 4.** Soft-rime particles motion

## 3.3 Hard-rime puncture mechanism

In strong gale conditions, hard-rime growth is simpler and more regular than soft-rime growth. When the rime particle condenses into a hard rime, there are the following characteristics: 1) The gale is so strong that other influences are negligible, resulting in different hard-rime agents snowballing in the same direction. 2) Due to the growth direction being the same, each rime agent can easily cross over, a phenomenon called rime puncture. 3) Like soft-rime agents, hard-rime agents increase in size as they grow, resulting in a greater probability of puncturing between agents in better growing conditions.

Therefore, this paper is inspired by the puncturing phenomenon and proposes a hard-rime puncture mechanism, which can be used to update the algorithm between agents, so that the particles of the algorithm can be exchanged and the convergence of the algorithm and the ability to jump out of the local optimum can be improved. The puncture phenomenon is shown in Figure 5, and the formula for replacement between particles is shown in Eq. (7).

|  |  |
| --- | --- |
| *,* | (7) |

where is the new position of the updated particle and is the -th particle of the best rime-agent in the rime-population . denotes the normalized value of the current agent fitness value, indicating the chance of the -th rime-agent being selected. is a random number in the range )-1,1(.

The pseudo-code for the hard-rime puncture mechanism is shown in Algorithm 2.

|  |
| --- |
| **Algorithm 2** Pseudo-code of the hard-rime puncture mechanism |
| Initialize the rime-population  Get the current optimal agent and optimal fitness  **While**  **For**  **For**  **If**  Position update according to the characteristics of the rime-particles by Eq. (7)  **End If**  **End For**  **End For**  Update the current optimal agent and optimal fitness    **End While** |



**Figure 5.** Hard-rime puncturing

## 3.4 Positive greedy selection mechanism

Typically, metaheuristic optimization algorithms have a greedy selection mechanism that replaces and records the best fitness value and the best agent after each update. The typical idea is to compare the updated fitness value of an agent with the global optimum, and if the updated value is better than the current global optimum, then the optimum fitness value is replaced, and the agent is recorded as the optimum. The advantage of such an operation is that it is simple and fast, but it does not help in the exploration and exploitation of the population and only serves as a record.

Therefore, the paper proposes an aggressive greedy selection mechanism for participating in population updates to improve global exploration efficiency. The specific idea is to compare the updated fitness value of an agent with the fitness value of an agent before the update, and if the updated fitness value is better than the value before the update, a replacement occurs, and also, the solution of both agents is replaced. On the one hand, this mechanism allows the population to continuously have good agents through active agent replacement, which improves the quality of the global solution. On the other hand, as the position of the agents of the population changes significantly with each iteration, there will inevitably be agents that are worse than the population before the update and are detrimental to the next iteration. Therefore, this operation can be used to ensure that the population evolves in a more optimal direction at each iteration.

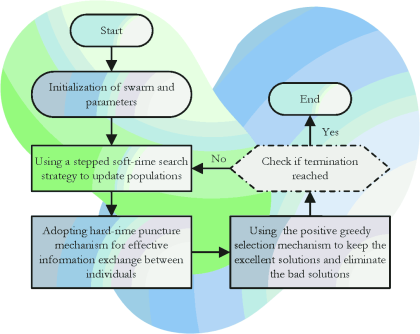
In this paper, the pseudo-code of the positive greedy selection mechanism for solving the minimum value problem, as an example, is shown in **Algorithm 3**.

|  |
| --- |
| **Algorithm 3** Pseudo-code of the positive greedy selection mechanism |
| Initialize the rime population  Get the current optimal agent and optimal fitness  **While**  **For**  **If** // Compare fitness values  = // Replace fitness values  = // Replace the current agent  **If**  // Compare optimal fitness values  = // Record optimal fitness values  = // Record the current optimal agent  **End If**  **End If**  **End For**    **End While** |

## 3.5 Proposed RIME algorithm

In summary, firstly, inspired by the motion of soft-rime particles in this section, a unique stepwise search and exploitation approach is designed to propose a soft-rime search strategy as the core optimization-seeking method of the algorithm. Immediately afterward, inspired by the crossover of hard-rime agents, a hard-rime puncture mechanism is proposed to achieve dimensional crossover interchange between ordinary and optimal agents, which is conducive to improving the solution accuracy of the algorithm. Finally, based on the greedy selection mechanism, an improved positive greedy selection mechanism is proposed to increase the diversity of the population and prevent the algorithm from falling into the local optimum as far as possible by changing the selection of optimal solutions. The overall structure of the algorithm in terms of pseudo-code and flow chart is shown in Algorithm 4 and Figure 6.

|  |
| --- |
| **Algorithm 4** Pseudo-code of RIME |
| Initialize the rime population  Get the current optimal agent and optimal fitness  **While** Coefficient of adherence  **If**  Update rime agent location by ***the soft-rime search strategy***  **End If**  **If**  Cross updating between agents by ***the hard-rime puncture mechanism***  **End If**  **If**  Select the optimal solution and replace the suboptimal solution using ***the positive greedy selection mechanism***  **End If**    **End While** |



**Figure 6.** Flowchart of RIME

1. Pictures obtained from <https://pixabay.com/> as copy right free images   
   (a) https://pixabay.com/photos/barbed-wire-frost-frozen-cold-ice-1938842/   
   (b) https://pixabay.com/photos/thuja-ice-winter-cold-frozen-6015613/ [↑](#footnote-ref-1)