Design and Application of Meta-Heuristic Algorithms for Engineering Optimization in Renewable Energy Systems

（再生可能エネルギーシステムにおけるエンジニアリング最適化のためのメタヒューリスティックアルゴリズムの設計と適用）

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CONTENTS

1 Background

- East Asian countries such as Japan, China, and South Korea are manufacturing powerhouses and have massive energy demands. As a result, countries are focusing their research on ensuring energy security, reducing their dependence on conventional energy, and promoting carbon neutrality.

- In recent years, Japan's energy security has been continuously challenged. The power crisis caused by the Great East Japan Earthquake and the soaring oil and gas prices triggered by the war in Russia and Ukraine have forced Japan to improve its **energy self-sufficiency**.

1 Background

- Electricity prices in Japan are rising on average by about 30% from 2021 to 2022.

- At the end of January, when the financial results of Japan's 10 major electric power companies for the April-December period of 2021 were released, six of them were already forecasting a net loss for the full year ending March 31, 2022. The subsequent invasion of Ukraine by Russia appears to have further inflated the procurement costs of these companies.

- 参考: [日本の電気料金3兆～5兆円増も　ウクライナ危機でエネルギー高騰]

主要10社中6社が最終赤字を予想
●国内電力会社の連結業績

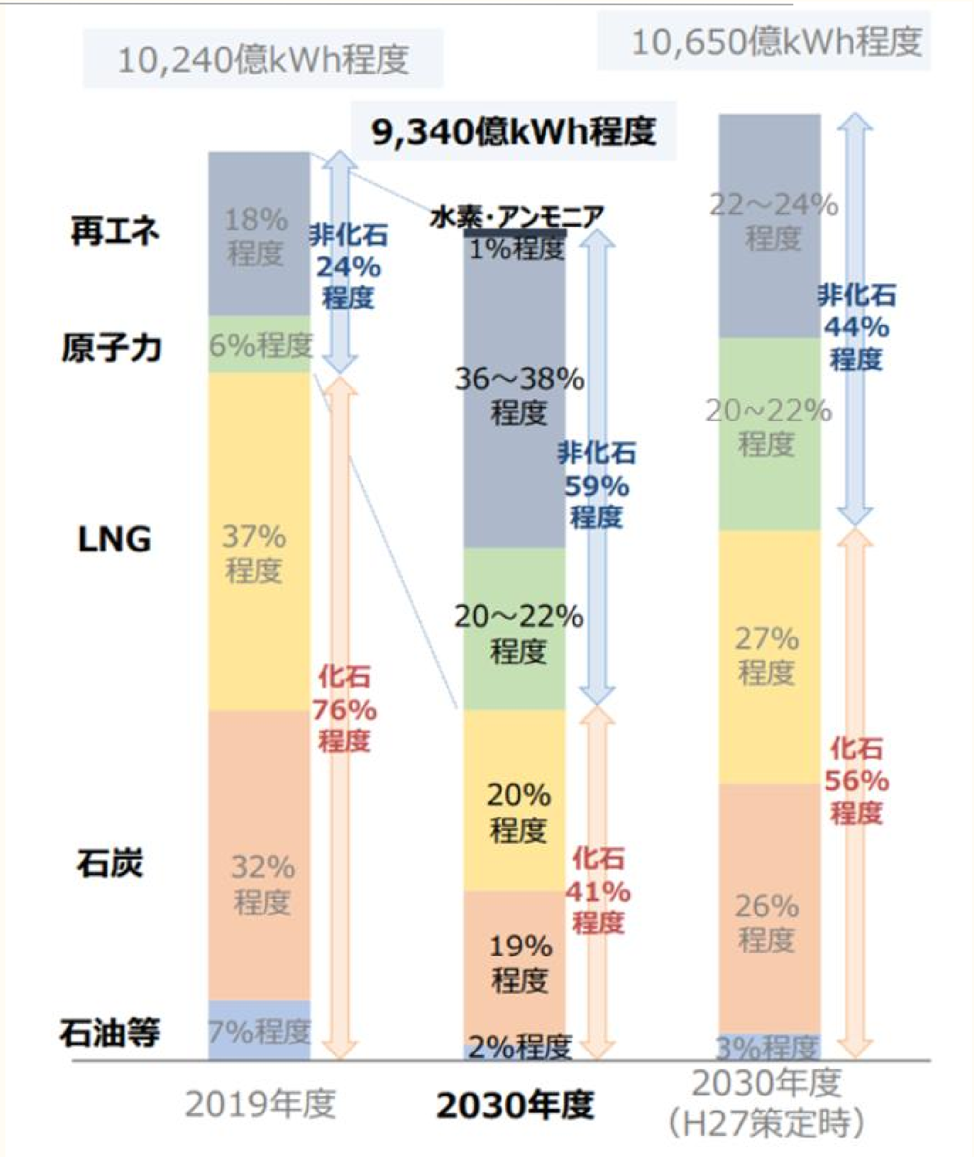
社名	最終損益（億円）	
	2021年3月期	22年3月期見通し
東京電力HD	1,808	▲410
中部電力	1,472	▲500
関西電力	1,089	650
北海道電力	361	70
九州電力	321	250
東北電力	293	▲450
中国電力	145	▲370
沖縄電力	83	17
北陸電力	68	▲70
四国電力	29	▲60

(注) 各社の決算資料などから編集部作成、▲は赤字

1 Background

- In order to achieve "carbon neutrality by 2050," the Japanese government announced the Sixth Basic Energy Plan in October 2021.

- The share of renewable energy was 22-24% in the previous plan, but has been raised to 36-38% in the current review. Nuclear power will continue to be maintained at 20-22%.

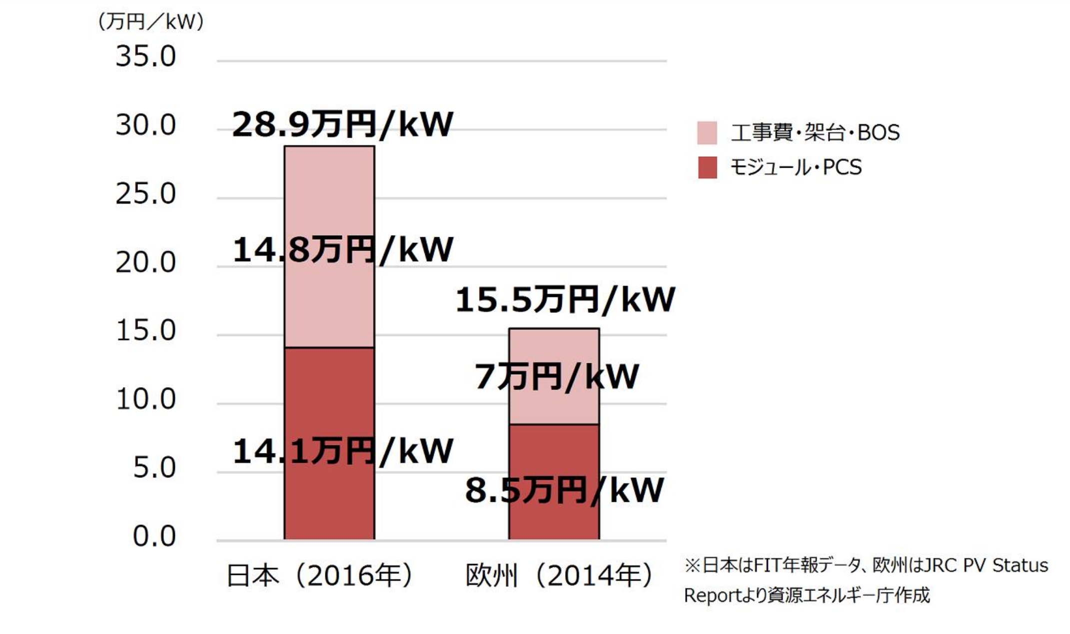


参考：経済産業省 資源エネルギー庁「2050年カーボンニュートラルを目指す　日本の新たな「エネルギー基本計画」」

1 Background

Compared to Europe and the U.S., where the price level remains the same, internationally traded solar panels and wind turbines are about 1.5 times more expensive in Japan, and the construction cost of installing them is also about 1.5 to 2 times higher, according to a survey.

参考：経済産業省・資源エネルギー庁 [「再エネのコストを考える」]

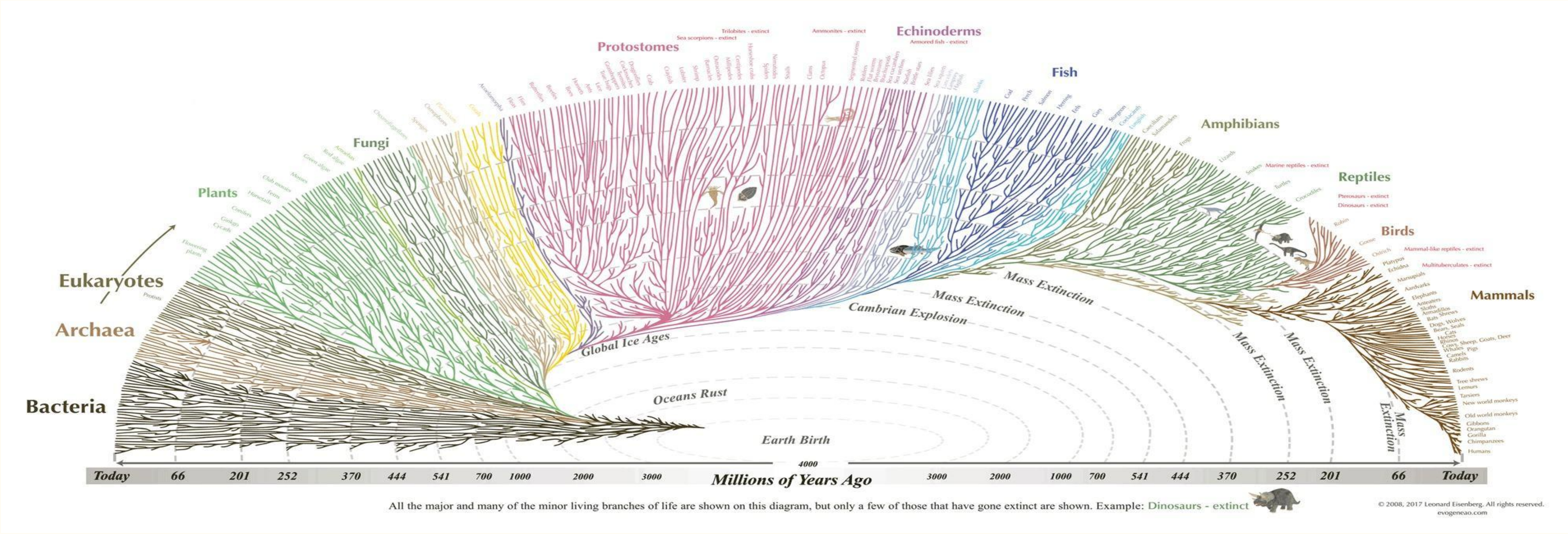


日欧の太陽光発電（非住宅）システム費用比較

The purpose of this study is to reduce the cost of renewable energy and increase energy production using the latest artificial intelligence optimization techniques.

Background – Meta-heuristic algorithms

- Meta-heuristic algorithms, as important optimization algorithms in the field of artificial intelligence, have great potential in the field of renewable energy.

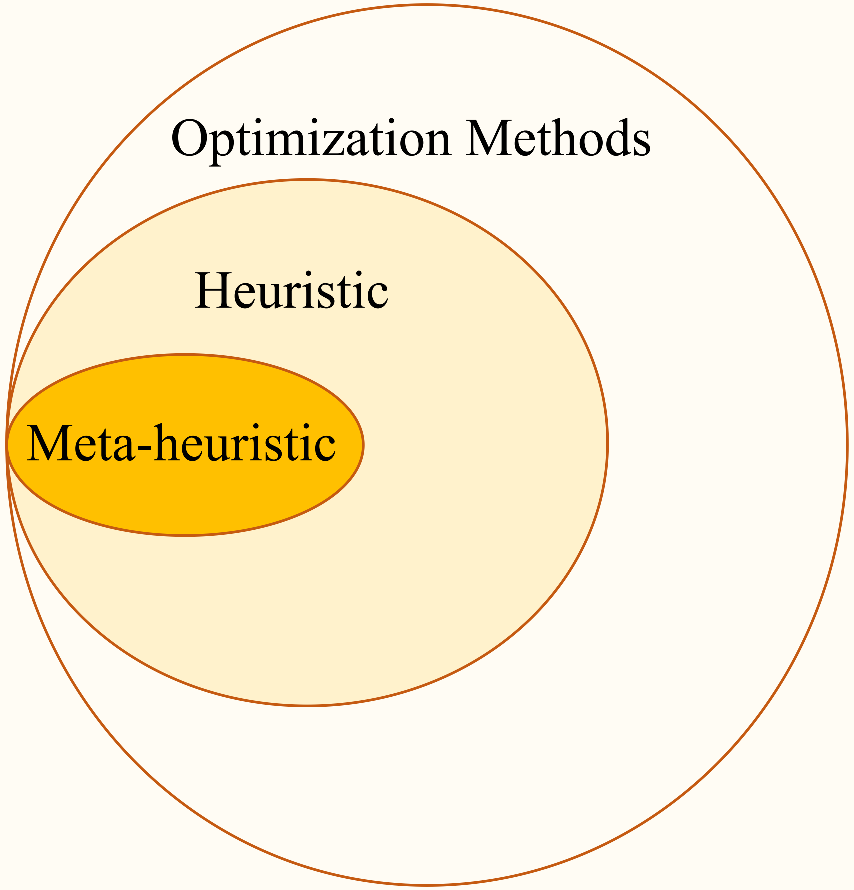


1 Background – Meta-heuristic algorithms

Addressing optimization problems is crucial in the study of a wide range of scientific and engineering issues [1].

- Heuristic algorithm [2]: One way of quickly arriving at a viable solution. It provides feasible solutions in a reasonable amount of time and space, but does not guarantee the best solution.

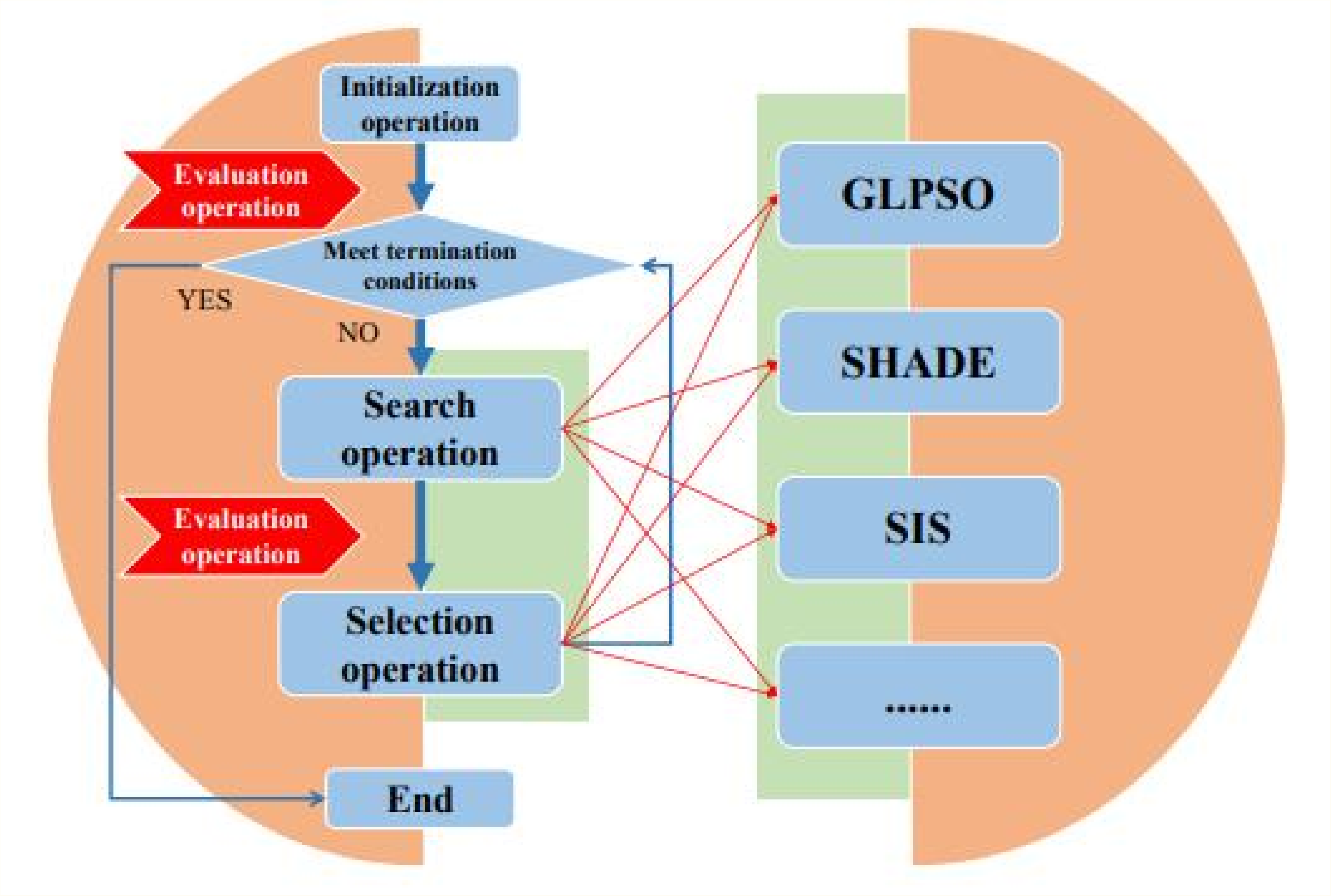
- Meta-heuristic algorithm (MHAs) [3]: It is a generalized heuristic method that can be applied to a broader range of situations than the specific conditions of a particular problem.



1. Chumburidze, M., Basheleishvili, I., & Khetsuriani, A. (2019). Dynamic programming and greedy algorithm strategy for solving several classes of graph optimization problems. BRAIN. Broad Research in Artificial Intelligence and Neuroscience, 10(1), 101-107.
2. Pearl, J. (1984). Heuristics: intelligent search strategies for computer problem solving.
3. Hussain, K., Salleh, M. N. M., Cheng, S., & Shi, Y. (2019). Metaheuristic research: a comprehensive survey. Artificial Intelligence Review, 52(4), 2191-2233.

Background – Meta-heuristic algorithms

A meta-heuristic algorithm typically contains an initialization operation, a search operation, an evaluation operation, and a selection operation.



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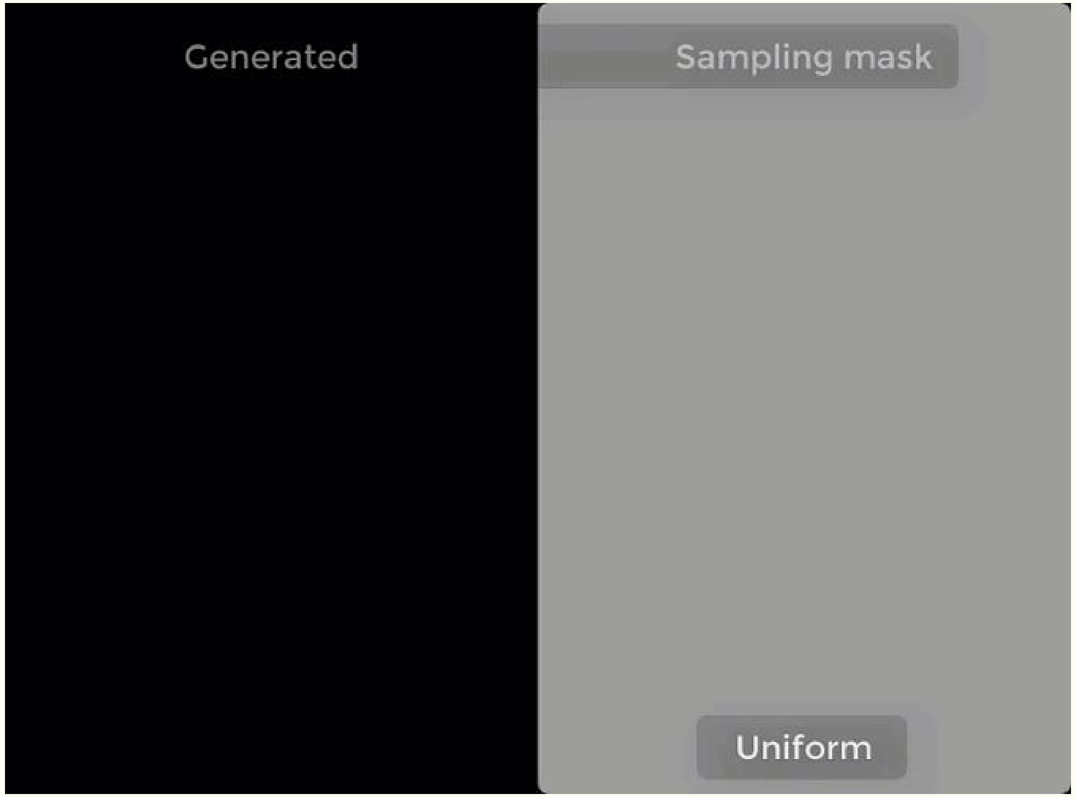
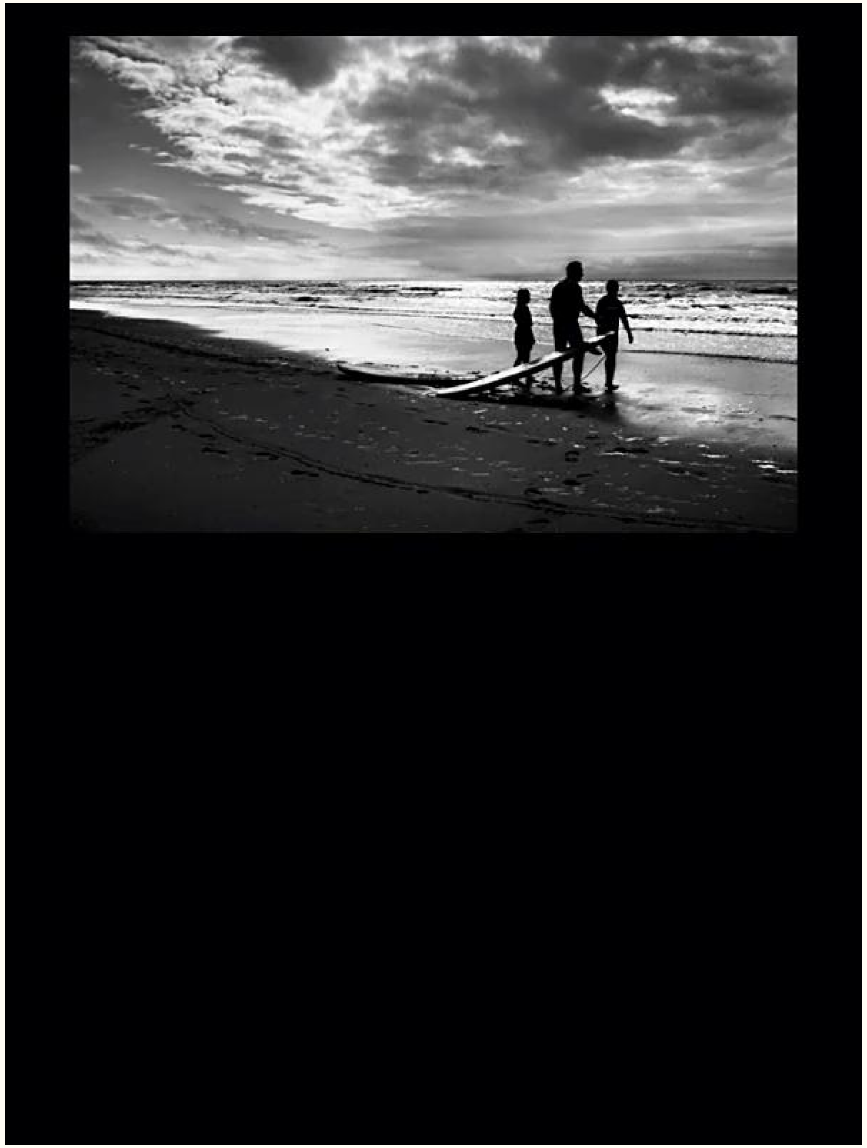
Background – Several interesting applications of MHAs

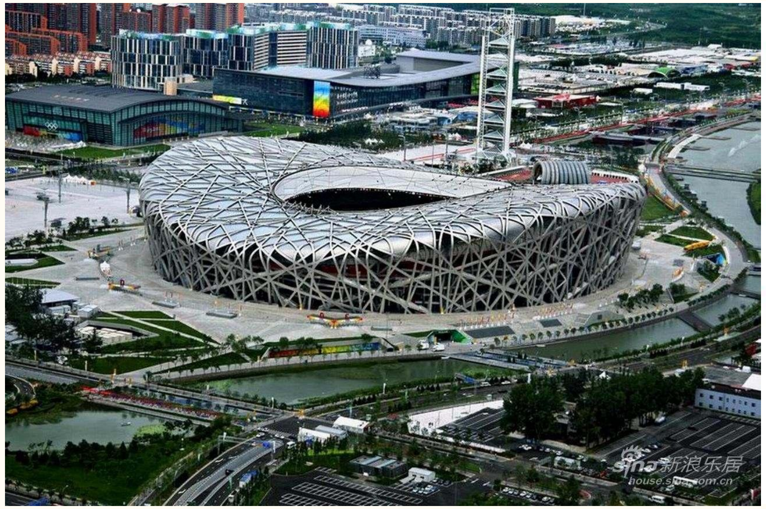
Anastasia Opara opened a project on GitHub: genetic drawing [4]. Its main purpose is to complete the painting work with the help of a genetic algorithm.

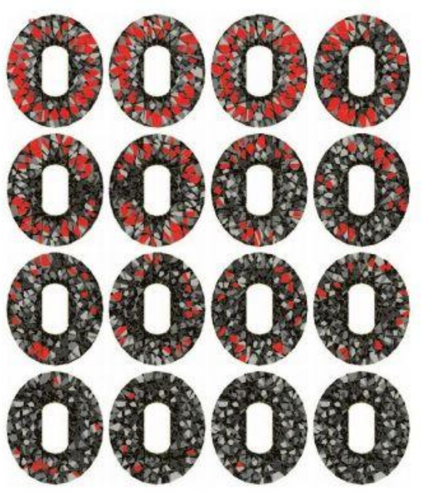




4.GitHub: anopara/genetic-drawing

1 Background – Several interesting applications of MHAs





The steel structure of the Beijing Bird's Nest gymnasium is iterated by a genetic algorithm, which is very stable. [5]

The unique aerodynamic nose of Shinkansen N700 series models in Japan is the result calculated by genetic algorithm. [5]

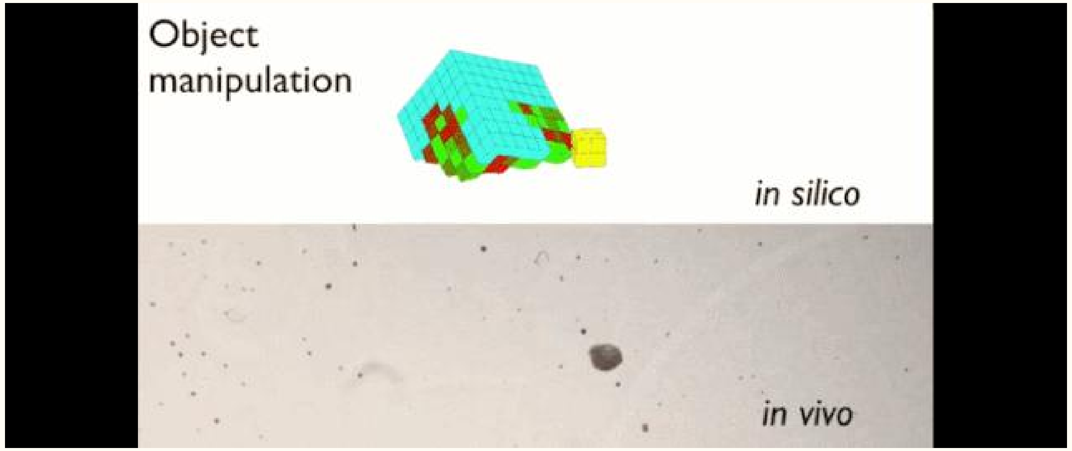
Series 700 Designed by human

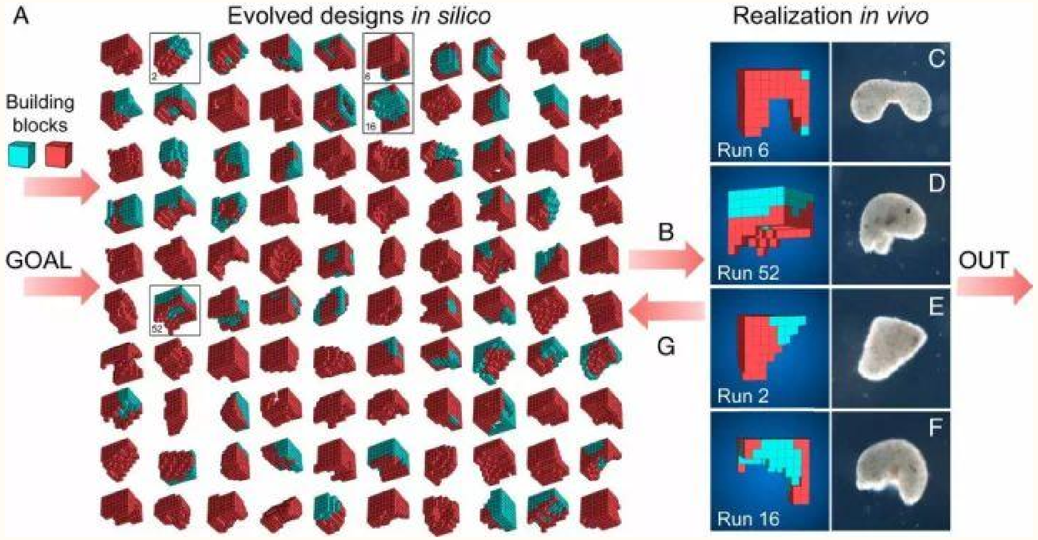
Series N700 Designed by EA

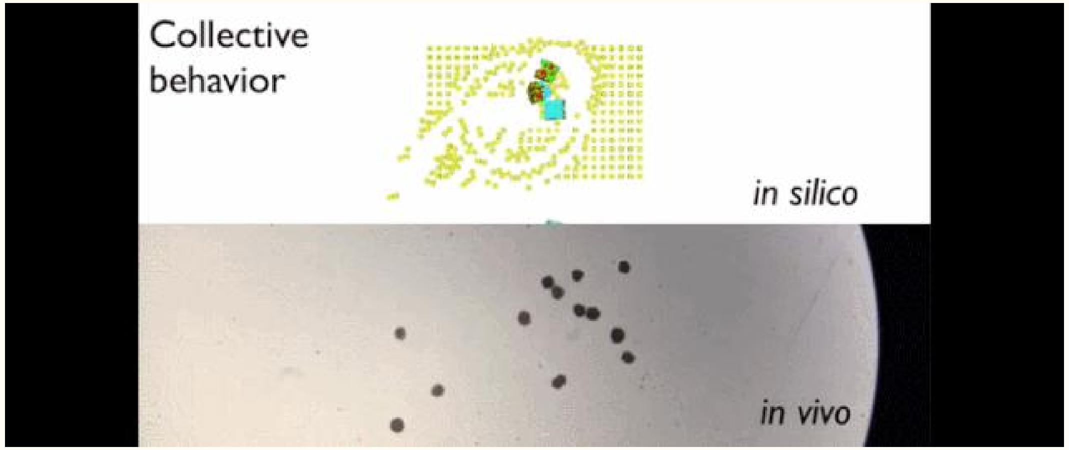
5. https://www.zhihu.com/question/26934313/answer/36716706

Background – Several interesting applications of MHAs

Recently, researchers at the University of Vermont have developed a biological robot called Xenobot using an evolutionary algorithm. It is composed of biological cells that can be programmed, modified, and moved freely. Even if it is cut, it can heal automatically. [6]



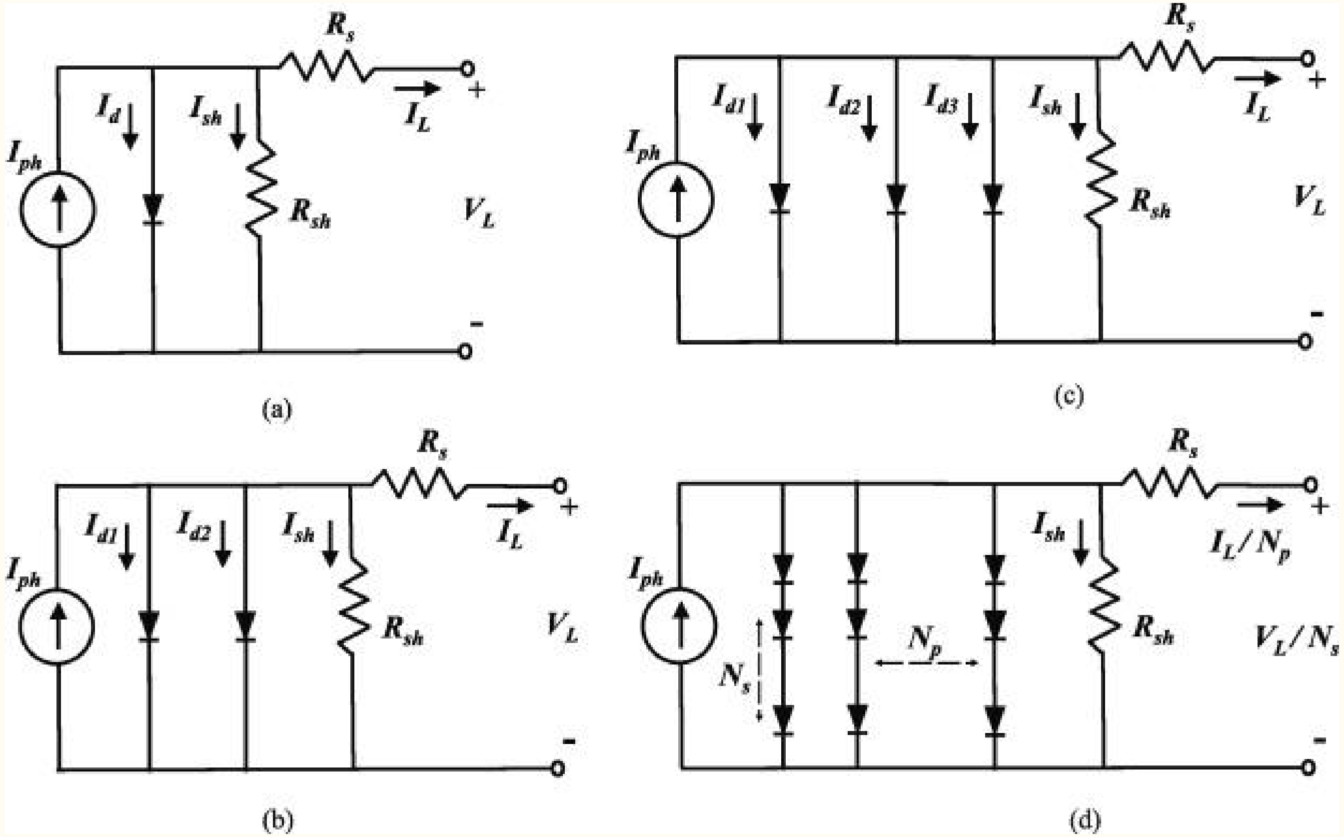




6. Kriegman, S., Blackiston, D., Levin, M., & Bongard, J. (2020). A scalable pipeline for designing reconfigurable organisms. *Proceedings of the National Academy of Sciences*, *117*(4), 1853-1859.

Background – Several applications of MHAs in the field of renewable energy

- Photovoltaic (PV) generation systems are vital to the utilization of the sustainable and pollution-free solar energy.
- In [7], researchers propose a state-of-the-art optimization method, namely, directional permutation differential evolution algorithm (DPDE), to tackle the parameter estimation of several kinds of solar PV models.

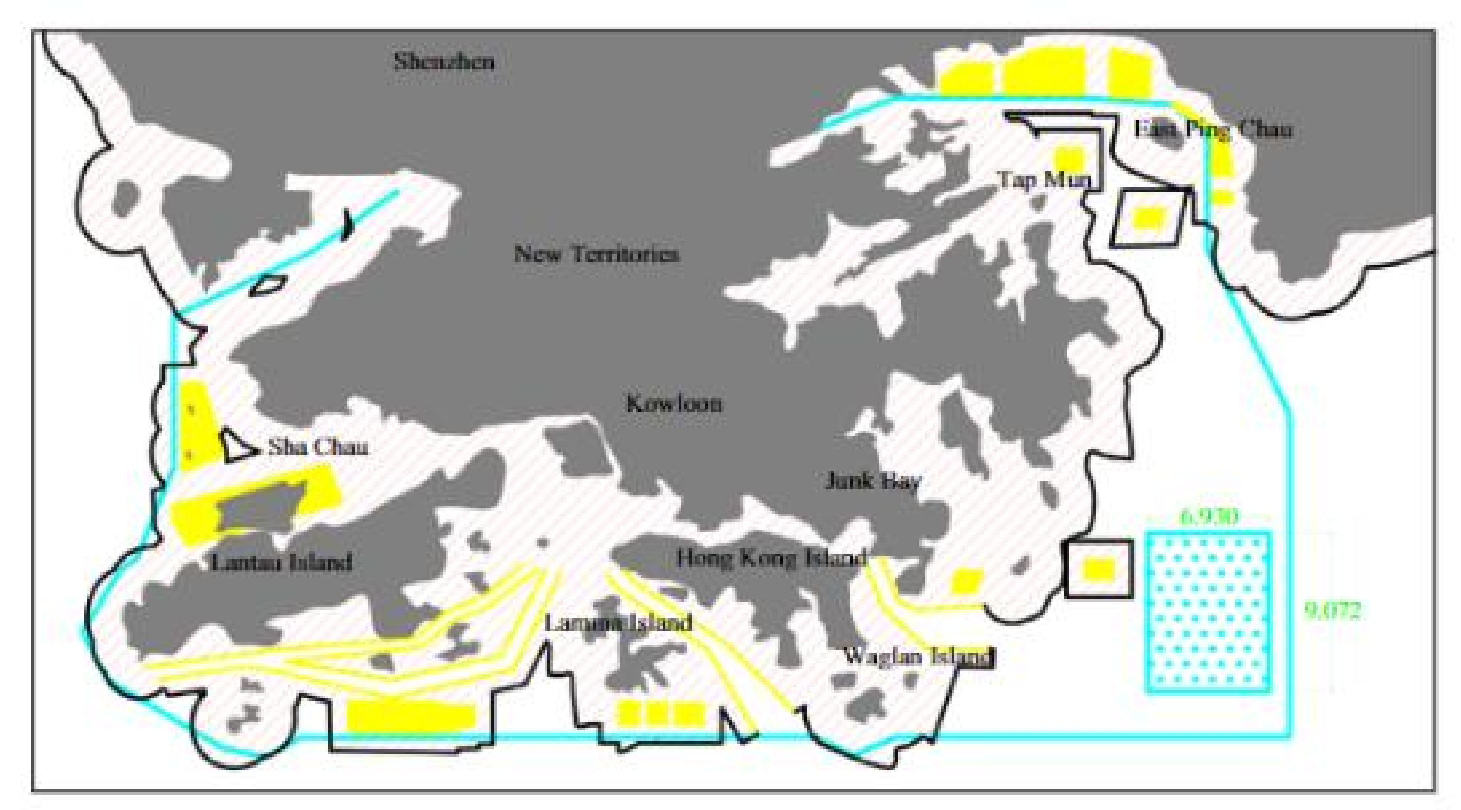


Equivalent circuit of PV: (a) single diode model, (b) double diode model, (c) triple diode model, and (d) PV module model.

7. Gao, S., Wang, K., Tao, S., Jin, T., Dai, H., & Cheng, J. (2021). A state-of-the-art differential evolution algorithm for parameter estimation of solar photovoltaic models. Energy Conversion and Management, 230, 113784. **(Highly Cited Paper, Top 1%)**

Background – Several applications of MHAs in the field of renewable energy

A case study of wind turbine layout optimization using the multi-population genetic algorithm [8] in a hypothetical offshore wind farm located in Hong Kong's southeast waters is attempted using 20 years of wind data from 1992 to 2011. The optimization result is beneficial for the assessment of the offshore wind power potential in Hong Kong.



Hong Kong territory map and location of the hypothetical offshore wind far

8. Gao, X., Yang, H., Lin, L., & Koo, P. (2015). Wind turbine layout optimization using multi-population genetic algorithm and a case study in Hong Kong offshore. Journal of Wind Engineering and Industrial Aerodynamics, 139, 89-99.

1 Background – Turbulence in the field of renewable energy

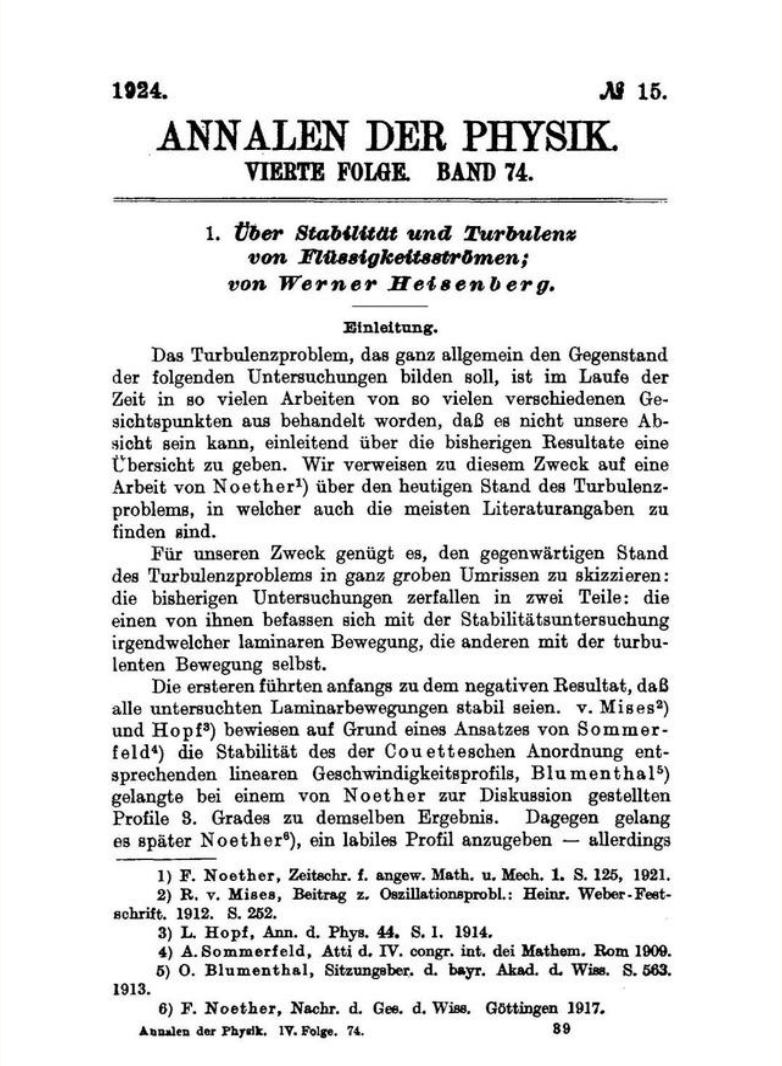
- In the field of renewable energy optimization, especially wind and wave energy engineering optimization studies, *turbulence* poses great difficulties.

- In fact, turbulence has been known for a long time. From Leonardo da Vinci's manuscripts to Van Gogh's "Starry Night", from《水图卷》 to 「神奈川沖浪裏」, painters have used their artistic brush to coincidentally depict visual images of turbulence.

Background – Turbulence in the field of renewable energy

- Turbulence is an extremely complex phenomenon of physics. On 1924, Heisenberg published a calculation entitled "Über Stabilität und Turbulenz von Flüssigkeitsströmen" [9] in the Annals of Physics.

- This problem is a classical problem of turbulence—determining the exact transition from laminar to turbulent flow—and one so difficult that Heisenberg provided only an approximate solution.



1924. №15.

ANNALEN DER PHYSIK.
VIERTE FOLGE. BAND 74.

1. *Über Stabilität und Turbulenz von Flüssigkeitsströmen;*
von Werner Heisenberg.

Einleitung.

Das Turbulenzproblem, das ganz allgemein den Gegenstand der folgenden Untersuchungen bilden soll, ist im Laufe der Zeit in so vielen Arbeiten von so vielen verschiedenen Gesichtspunkten aus behandelt worden, daß es nicht unsere Absicht sein kann, einleitend über die bisherigen Resultate eine Übersicht zu geben. Wir verweisen zu diesem Zweck auf eine Arbeit von Noether[1]) über den heutigen Stand des Turbulenzproblems, in welcher auch die meisten Literaturangaben zu finden sind.

Für unseren Zweck genügt es, den gegenwärtigen Stand des Turbulenzproblems in ganz groben Umrissen zu skizzieren: die bisherigen Untersuchungen zerfallen in zwei Teile: die einen von ihnen befassen sich mit der Stabilitätsuntersuchung irgendwelcher laminaren Bewegung, die anderen mit der turbulenten Bewegung selbst.

Die ersteren führten anfangs zu dem negativen Resultat, daß alle untersuchten Laminarbewegungen stabil seien. v. Mises[2]) und Hopf[3]) bewiesen auf Grund eines Ansatzes von Sommerfeld[4]) die Stabilität des der Couetteschen Anordnung entsprechenden linearen Geschwindigkeitsprofils, Blumenthal[5]) gelangte bei einem von Noether zur Diskussion gestellten Profile 3. Grades zu demselben Ergebnis. Dagegen gelang es später Noether[6]), ein labiles Profil anzugeben — allerdings

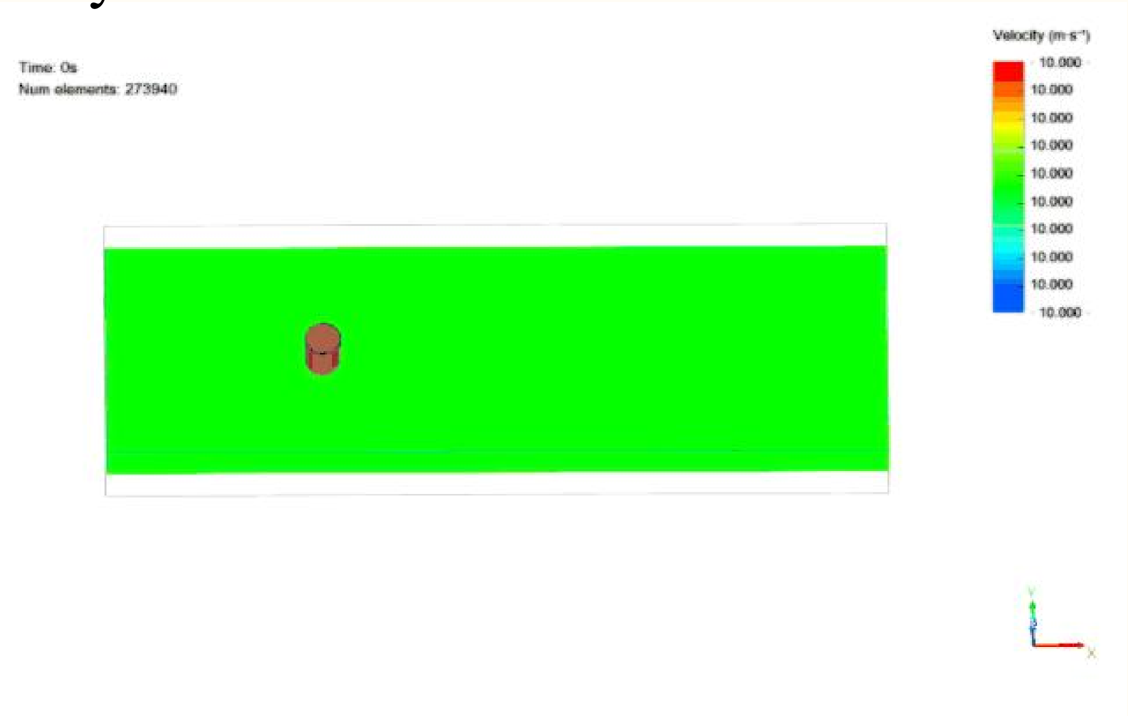
1) F. Noether, Zeitschr. f. angew. Math. u. Mech. 1. S. 125, 1921.
2) R. v. Mises, Beitrag z. Oszillationsprobl.: Heinr. Weber-Festschrift. 1912. S. 252.
3) L. Hopf, Ann. d. Phys. 44. S. 1. 1914.
4) A. Sommerfeld, Atti d. IV. congr. int. dei Mathem. Rom 1909.
5) O. Blumenthal, Sitzungsber. d. bayr. Akad. d. Wiss. S. 563. 1913.
6) F. Noether, Nachr. d. Ges. d. Wiss. Göttingen 1917.

Annalen der Physik. IV. Folge. 74. 39

[9] Werner Heisenberg. Über Stabilität und Turbulenz von Flüssigkeitsströmen.Annalen der Physik, 379(15):577–627, 1924.

1 Background – Reasons for adopting MHAs

- Traditional methods for solving problems related to wind farm layout optimization and position optimization of wave energy converters consume a large amount of human and computational resources due to the complexity of turbulence.



- Therefore, since the MHAs are able to provide a feasible solution to the problem at an acceptable cost (in terms of computational time and space), they become an important tool for solving the above problems. [10]

10. Liu, Z., Peng, J., Hua, X., & Zhu, Z. (2021). Wind farm optimization considering non-uniformly distributed turbulence intensity. Sustainable Energy Technologies and Assessments, 43, 100970.

Background – Research contributions

- **Contribution 1:** To design superior algorithms to handle the position optimization problems of wave energy converters (WECP) and wind farm layout optimization problems (WFLOP) in order to obtain higher energy output.

- **Contribution 2:** To try to identify a design guidance scheme for MHAs based on complex systems theory in order to reduce the time and labor cost required for algorithm design.

In this study, we successively designed the spatial information sampling algorithm (SIS) and the improved spherical evolution (ISE).

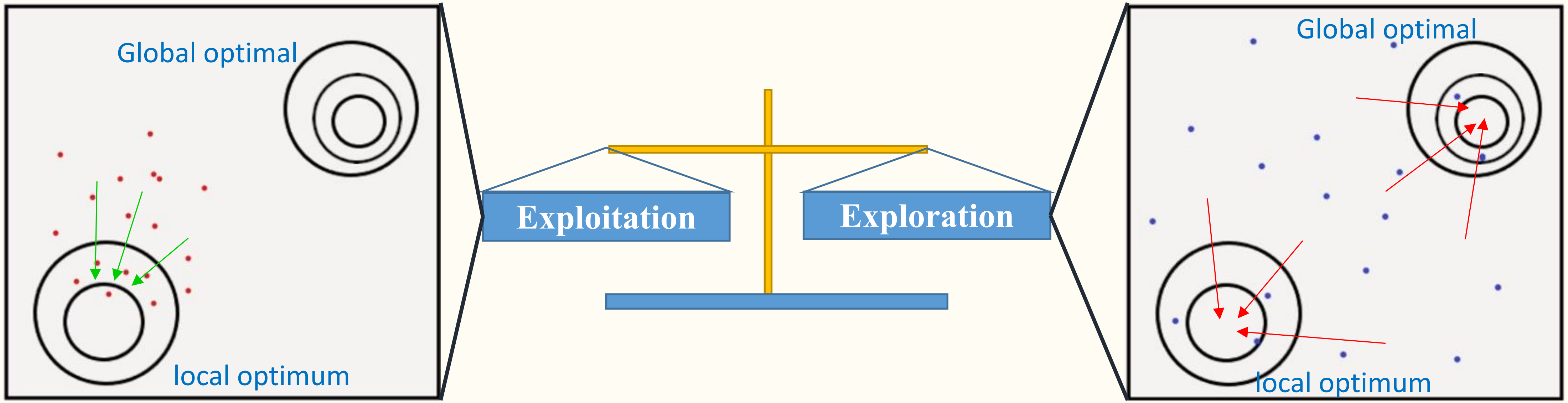
CONTENTS

2 Spatial information sampling algorithm- Theoretical basis

Because of MHAs' superior performance in addressing optimization problems, how to design a MHA with superior performance has become the focus of research in MHAs' community. In recent decades, researchers appear to have concluded that maintaining a balance between exploitation and exploration is critical for improving MHAs' performance. [11]

Exploitation: The idea of focusing the search process on promising areas of the solution space. (Easy to fall into local optimal)

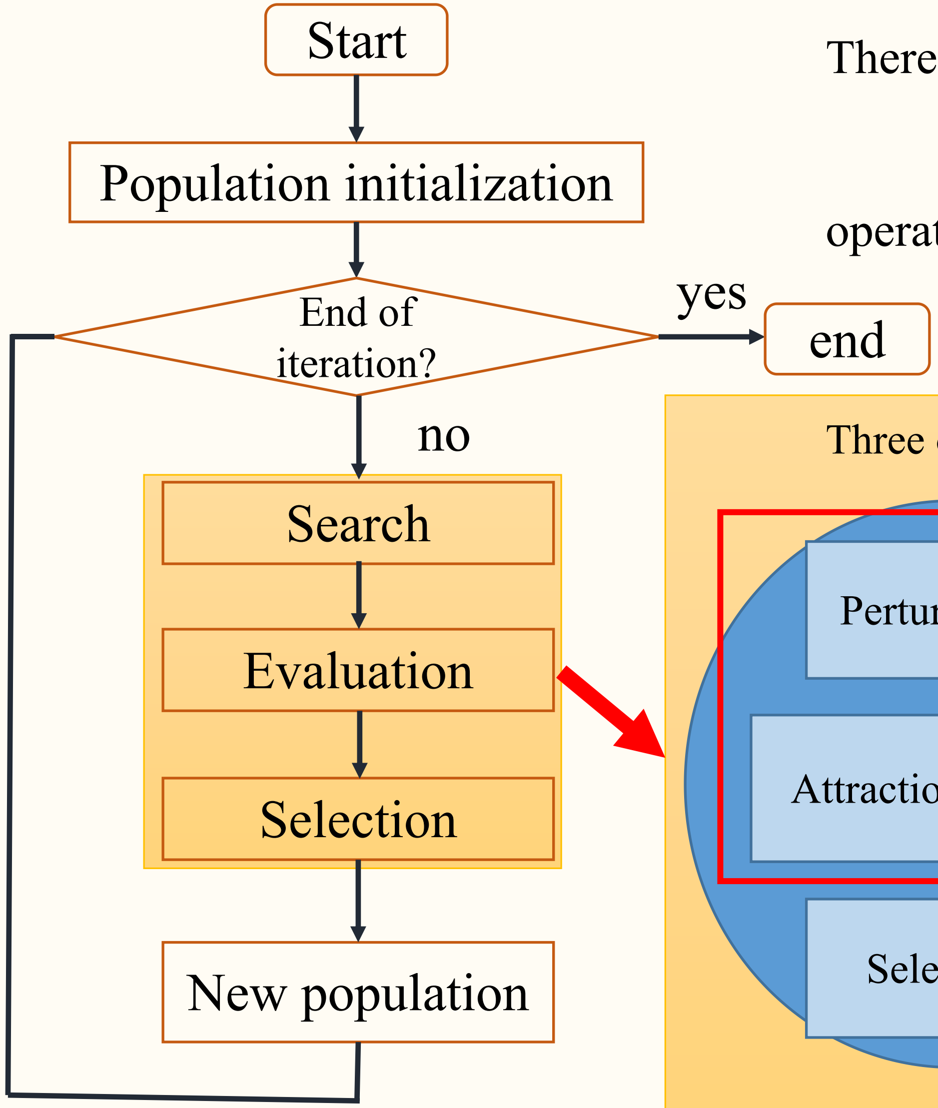
Exploration: The ability of a search algorithm to discover a diverse array of solutions spread across different regions of the search space. (The convergence ability becomes weak)



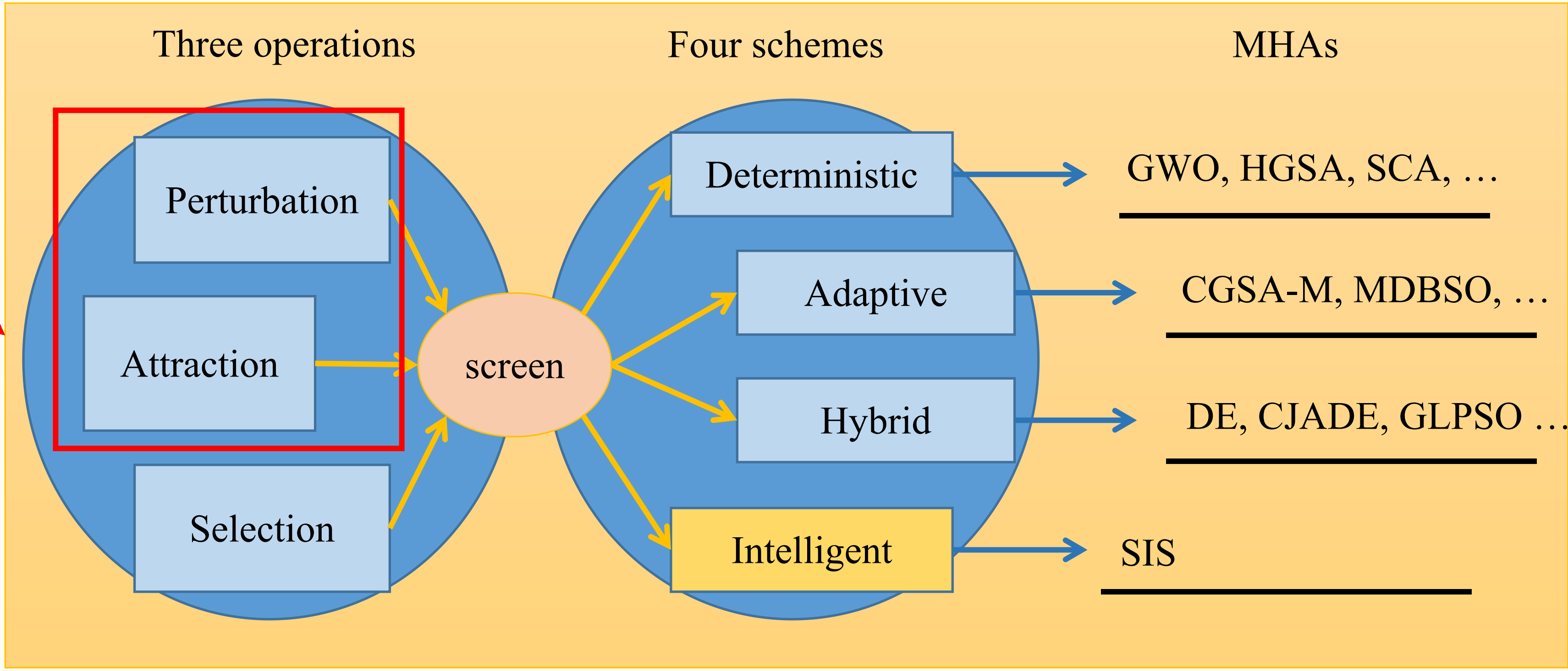
11. Črepinšek, M., Liu, S. H., & Mernik, M. (2013). Exploration and exploitation in evolutionary algorithms: A survey. ACM computing surveys (CSUR), 45(3), 1-33.

Spatial information sampling algorithm- Theoretical basis

There are three main ways to realize exploitation and exploration operations: selection, attraction, and perturbation operations.



The main steps of MHAs

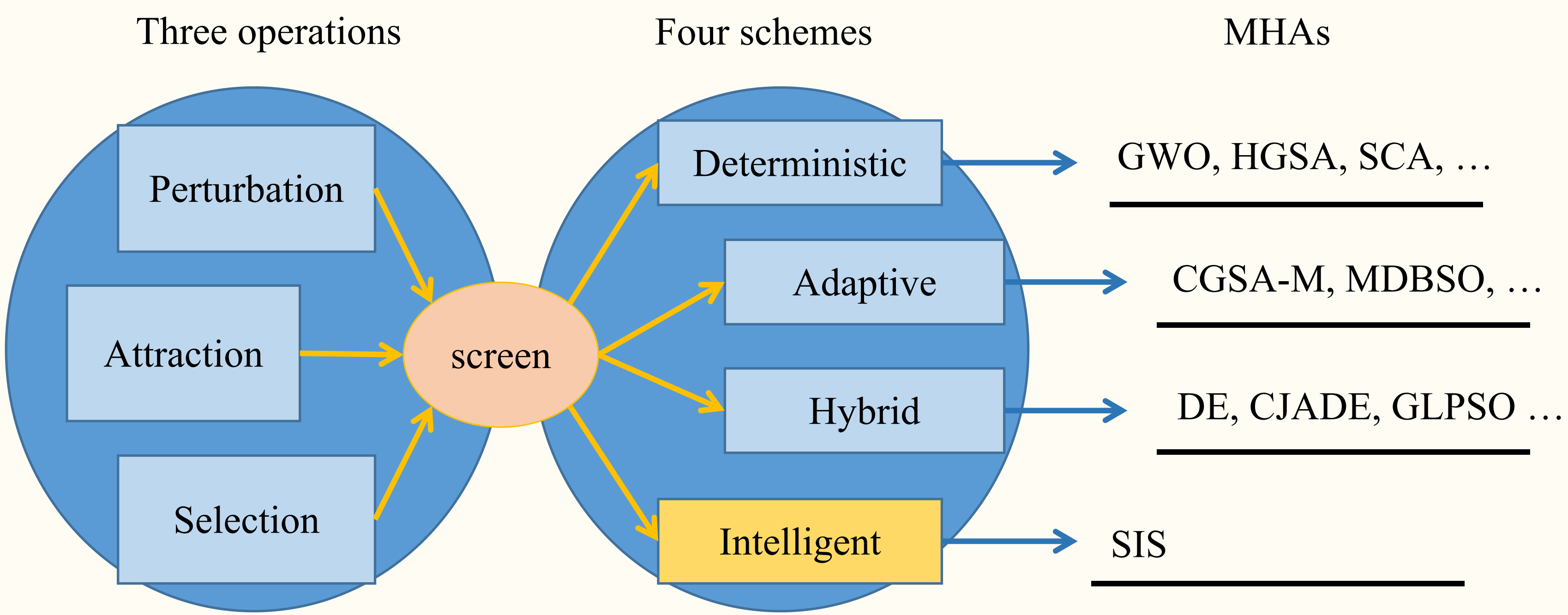


The main classes of MHAs

2 Spatial information sampling algorithm- Theoretical basis

In essence, the balance of exploitation and exploration of MHAs is realized by combining selection, attraction, or perturbation operations. We divide the main combination methods into the following three types: deterministic, adaptive, and hybrid schemes.

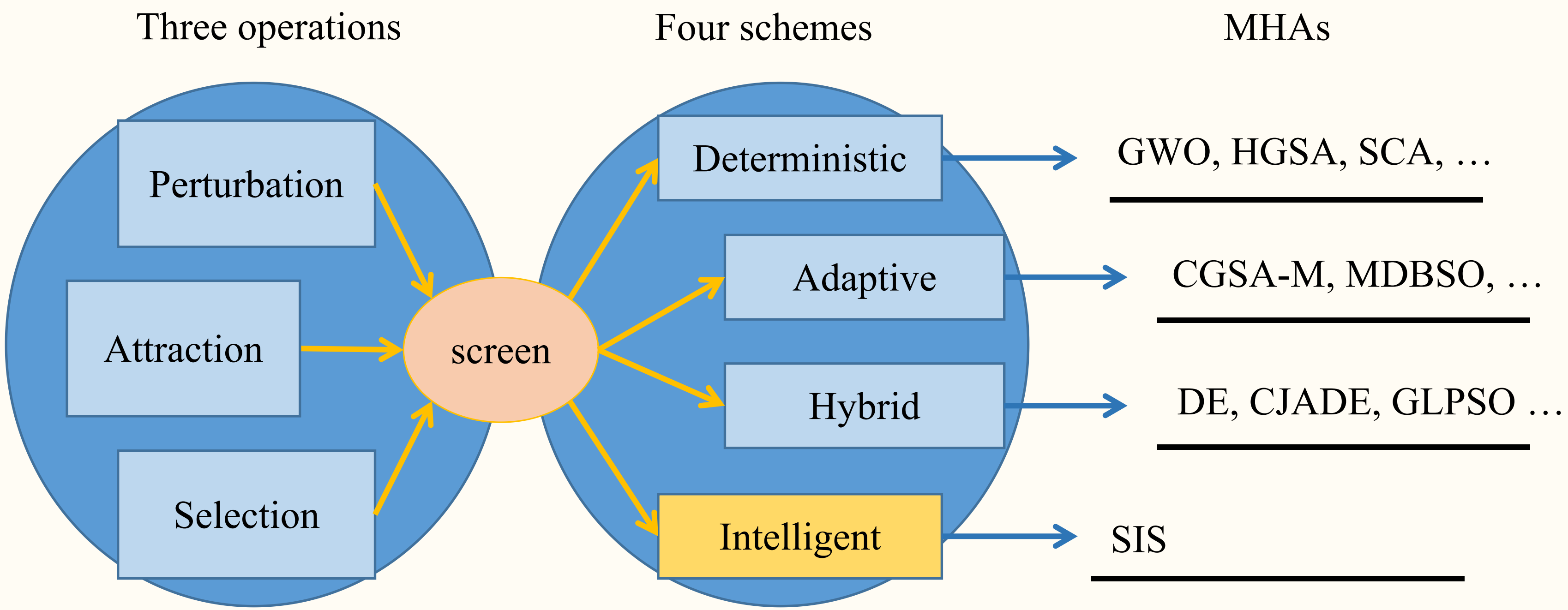
However, these schemes are both prior experience-based schemes that restrict the acquisition and application of information by the algorithm itself, causing the algorithm to stray from the path of "intelligence".



Spatial information sampling algorithm- Theoretical basis

To address the aforementioned problems, this study proposes an ***intelligent scheme*** that aims to give the algorithm more decision-making authority to determine when to perform exploration or exploitation.

Thus, a ***spatial information sampling (SIS)*** algorithm that uses an intelligent scheme is proposed.



2 Spatial information sampling algorithm- Basic idea of SIS

In this study, we regard the problem to be optimized as a space in which the SIS population swims to find the global best. The entire SIS population is referred to as X, and it is divided into two sub-populations, L and R, with individuals in L distributed along the population's periphery and R distributed evenly.

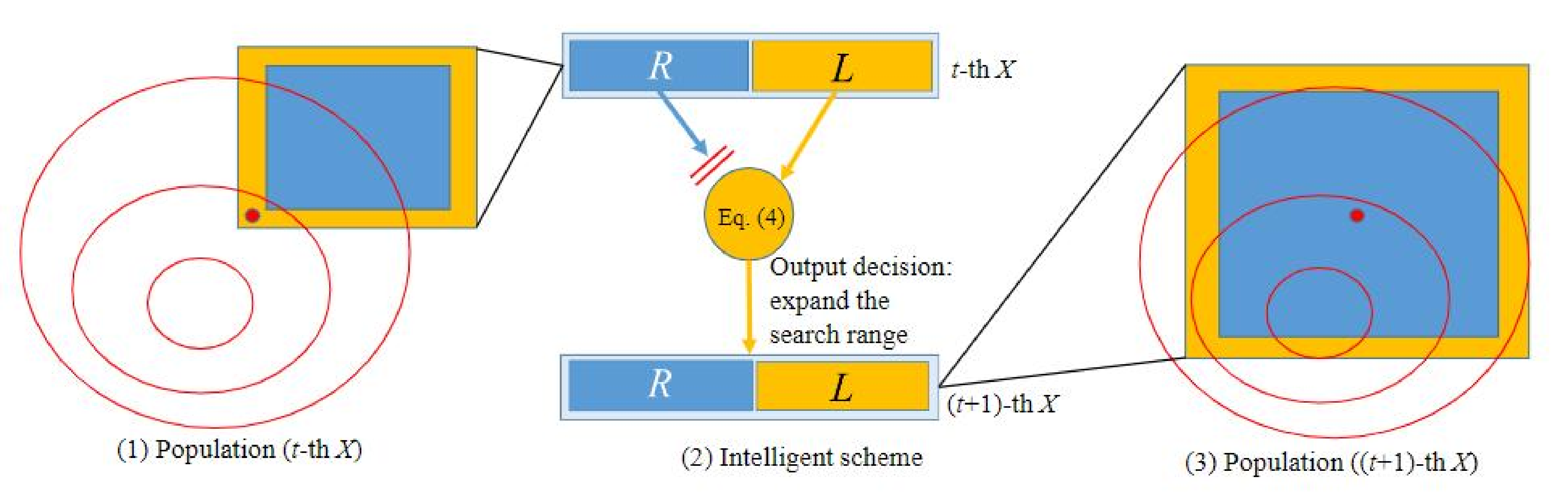


Fig. 1

2 Spatial information sampling algorithm- Basic idea of SIS

In this study, we regard the problem to be optimized as a space in which the SIS population swims to find the global best. The entire SIS population is referred to as *X*, and it is divided into two sub-populations, *L* and *R*, with individuals in *L* distributed along the population's periphery and *R* distributed evenly.

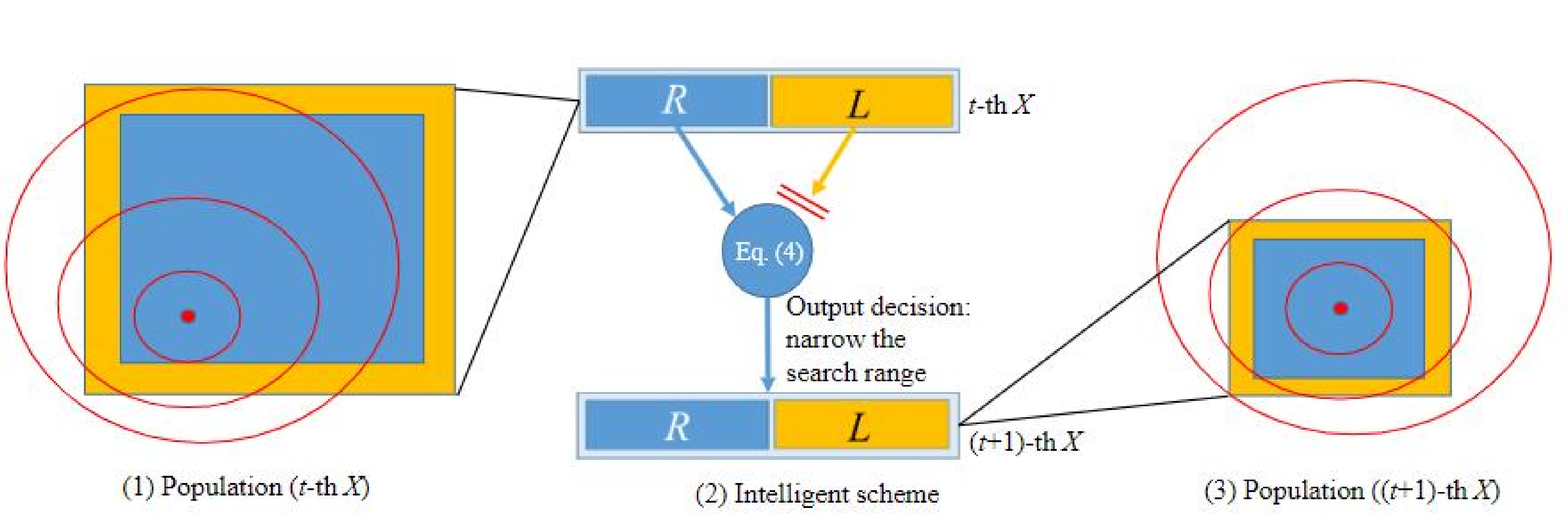


Fig. 2

2 Spatial information sampling algorithm - Basic components of SIS

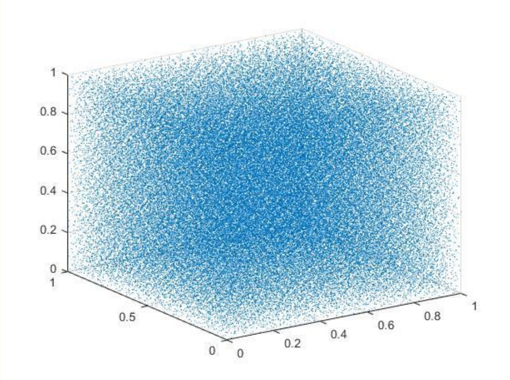
The generation process of individuals x_i in *R* and *L* is written as:

$$\delta x^t = \frac{U_d - F_d}{N_0}, \quad t = 1, \quad d = [1, 2, ..., D] \qquad (1)$$

$$\begin{cases} x_{i,d}^{t+1} = (2 \cdot r_{i,d} - 1) \cdot \delta x_d^t + o^t & x_i \in R \\ x_{i,d}^{t+1} = (2 \cdot l_{i,d} - 1) \cdot \delta x_d^t + o^t & x_i \in L \end{cases} \qquad (2)$$

$$l_{i+1,d} = r \cdot l_{i,d} \cdot (1 - l_{i,d}), \quad i = [1, 2, ..., N/2] \qquad (3)$$

- $\delta x^t = [\delta x_1, \delta x_2, ..., \delta x_D]$ denotes a discrete step, representing the distance between each individual in each dimension.
- The sub-population generated by the random sequence is called *R*. The other one generated by the Logistic map (a kind of chaotic map) is referred to as *L*.
- where U_d and F_d are the upper and lower limits of the solution space in the d-dimension, respectively.
- where $r_{i,d}$ is generated by the random sequence and $l_{i,d}$ is generated by the Logistic map



Distribution graph of R.

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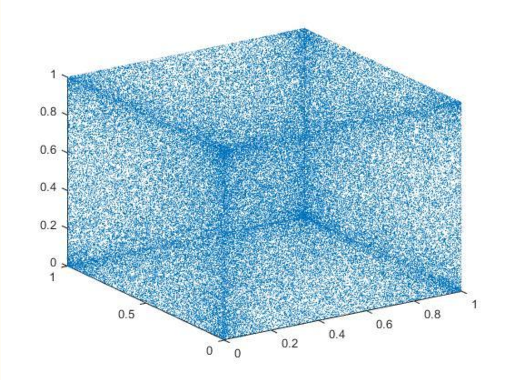

Distribution graph of L.

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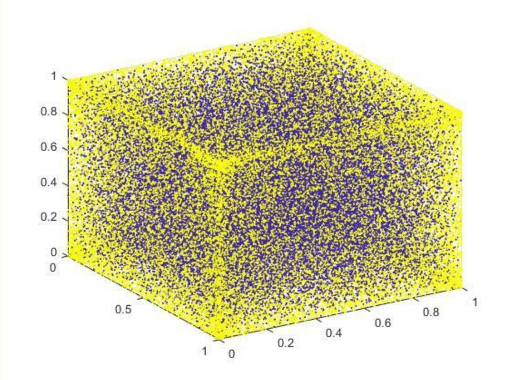


Distribution graph of X.

2 Spatial information sampling algorithm - The realization of intelligent scheme

Without loss of generality, the optimization of a minimization problem is considered.

After generating *X*, the fitness values of all individuals are calculated, and thereafter those with the best value in *R* and *L* are denoted by *Rm* and *L*m, respectively. When f(*Lm*)< f(*Rm*), δx^{t+1} is increased. When f(*Lm*)>f(*Rm*), δx^{t+1} is reduced.

$$(c)\begin{cases} (a)\begin{cases}\delta x^{t+1} = (1+b)\cdot\delta x^{t} \\ o^{t+1} = L_m\end{cases} & \text{if } f(R_m) > f(L_m) \\ (b)\begin{cases}\delta x^{t+1} = (1-b)\cdot\delta x^{t} \\ o^{t+1} = R_m\end{cases} & \text{if } f(R_m) < f(L_m)\end{cases} \tag{4}$$

where *b* is the parameter for adjusting the distance between individuals. The optimal individual is represented as *o*.

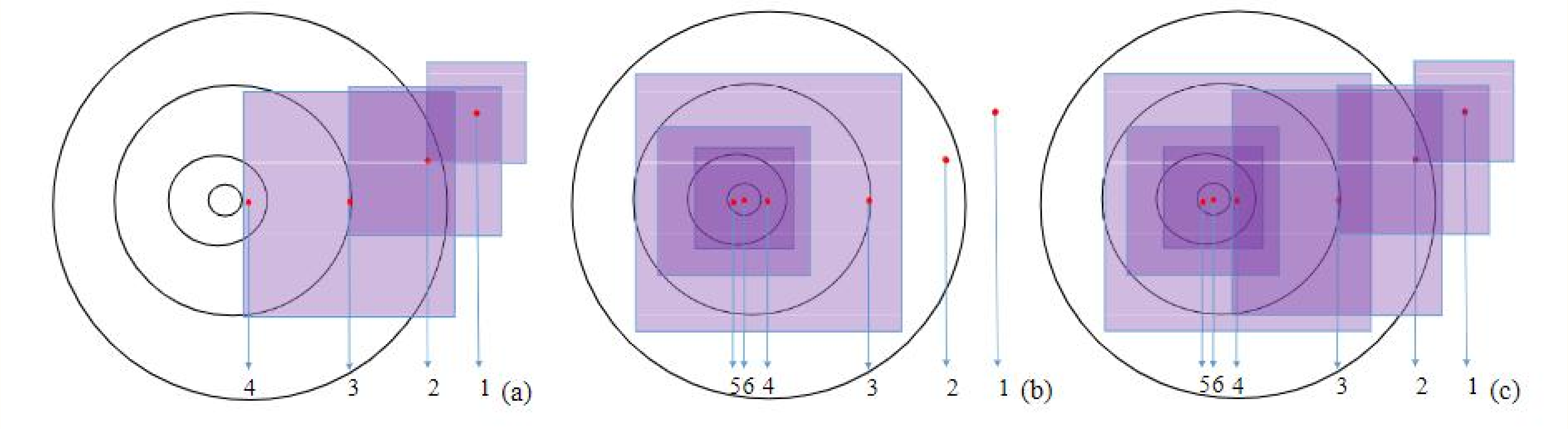
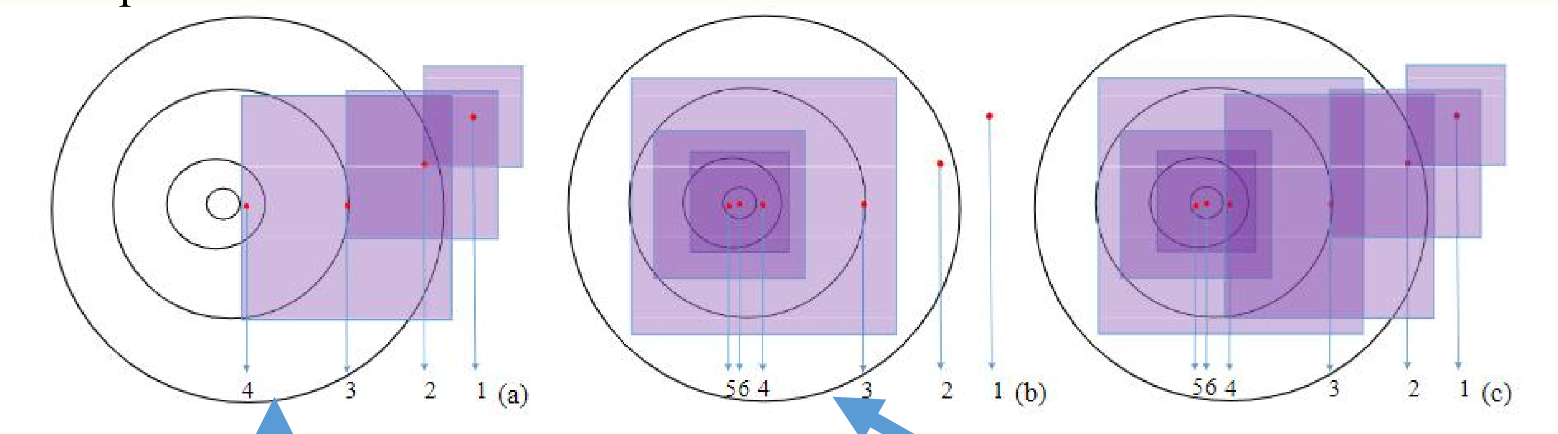
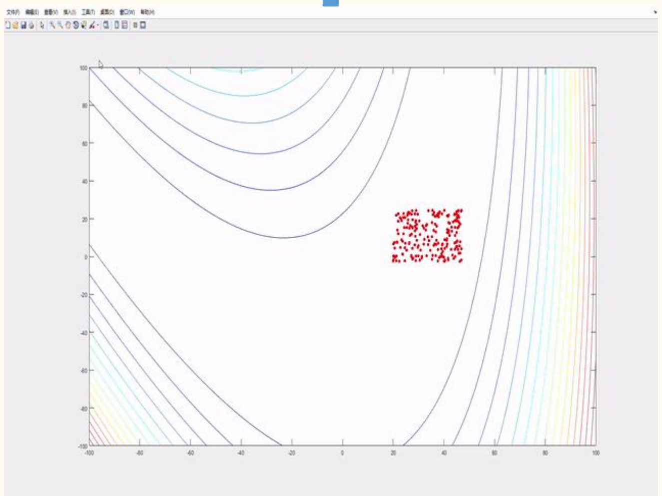


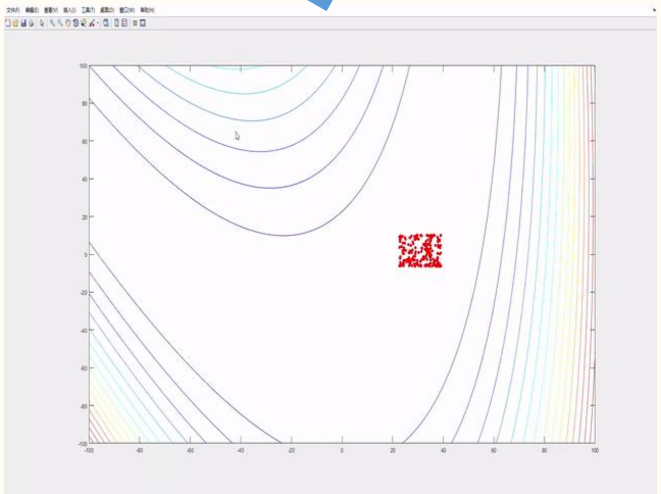
Fig. 3 Two-dimensional schematic diagram of SIS in the iterative process.

2 Spatial information sampling algorithm- Iterative process of SIS

Fig. 3 Two-dimensional schematic diagram of SIS in the iterative process.



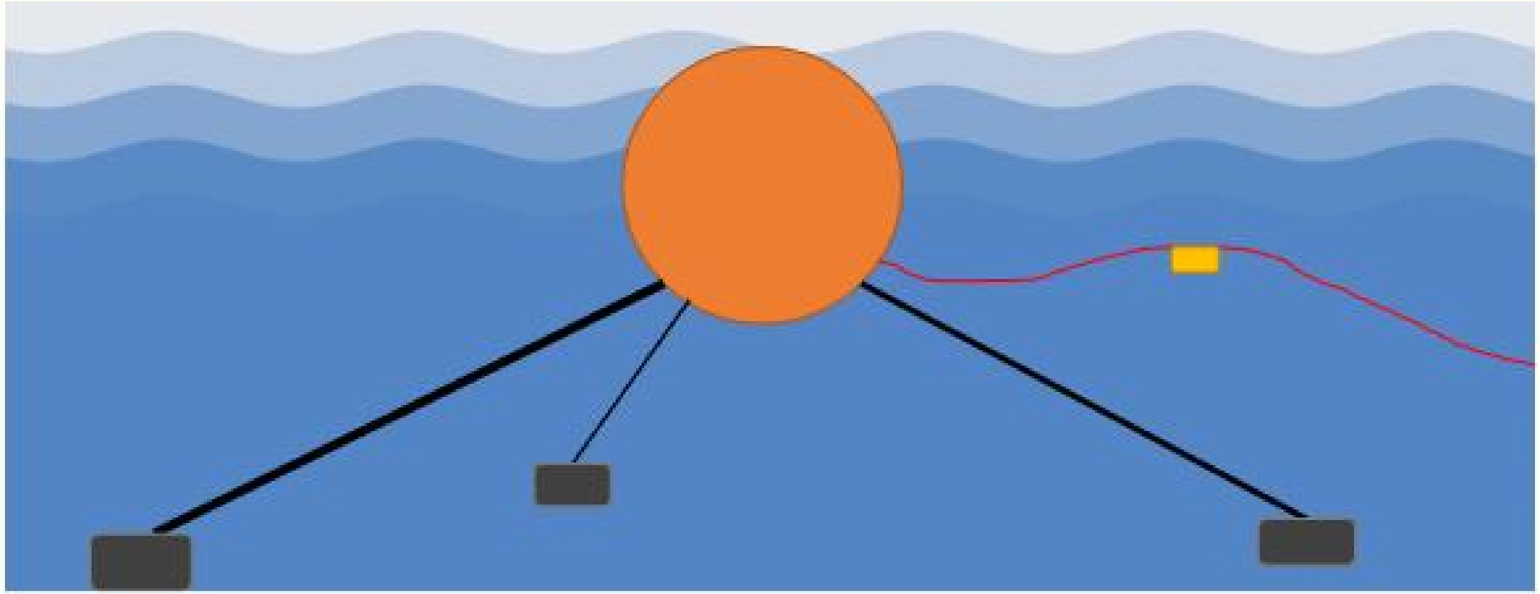




2 Spatial information sampling algorithm- The main steps of SIS

```
Algorithm 1: Pseudocode of SIS
begin
    /*Algorithm initialization */
    Initialize parameter b and randomly initialize N individuals
    Calculate δx^1 by Eq. (1)
    f(X) = evaluate(X)
    Find out the optimal individual o in the population
    while Terminal Condition do
        /*Population construction*/
        for i = 1 : N/2 do
            for d = 1 : D do
                Eq. (2)
        Boundary detection
        /*Intelligent scheme */
        f(X) = evaluate(X)
        Looking for the individual R_m and L_m with the best fitness value in R and L
        Through Eq. (4), update δx and o
```

2 Spatial information sampling algorithm - Experimental Results



Because of the high energy density of waves, wave energy is one of the most promising forms of renewable energy currently available. [12] In this section, we attempt to use SIS to optimize the placement of wave energy converters [13], and we compare SIS with an improved differential evolution algorithm (IDE) [14] modified specifically for this problem under four real wave regimes (Perth, Adelaide, Tasmania, and Sydeny).

12. Drew, B., Plummer, A. R., & Sahinkaya, M. N. (2009). A review of wave energy converter technology. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 223(8), 887-902.
13. Sergiienko, N. Y., Cazzolato, B. S., Ding, B., & Arjomandi, M. (2016, October). Three-tether axisymmetric wave energy converter: estimation of energy delivery. In Proc. 3rd Asian Wave and Tidal Energy Conference (AWTEC), Singapore (pp. 23-25).
14. Fang, H. W., Feng, Y. Z., & Li, G. P. (2018). Optimization of wave energy converter arrays by an improved differential evolution algorithm. Energies, 11(12), 3522.

2

Spatial information sampling algorithm - Experimental results

	Tasmania		Adelaide		Perth		Sydney	
	SIS	IDE	SIS	IDE	SIS	IDE	SIS	IDE
max	**1.341E+06**	1.095E+06	**8.349E+05**	4.023E+05	**7.985E+05**	3.996E+05	**4.232E+05**	4.127E+05
min	**1.273E+06**	1.095E+06	**7.536E+05**	4.023E+05	**7.277E+05**	3.996E+05	4.100E+05	4.127E+05
mean	**1.311E+06**	1.095E+06	**8.055E+05**	4.023E+05	**7.656E+05**	3.996E+05	4.120E+05	4.127E+05
1	1.277E+06	1.095E+06	8.287E+05	4.023E+05	7.729E+05	3.996E+05	4.123E+05	4.127E+05
2	1.341E+06	1.095E+06	8.287E+05	4.023E+05	7.738E+05	3.996E+05	4.110E+05	4.127E+05
3	1.273E+06	1.095E+06	7.779E+05	4.023E+05	7.457E+05	3.996E+05	4.105E+05	4.127E+05
4	1.300E+06	1.095E+06	7.536E+05	4.023E+05	7.985E+05	3.996E+05	4.103E+05	4.127E+05
5	1.336E+06	1.095E+06	7.611E+05	4.023E+05	7.277E+05	3.996E+05	4.232E+05	4.127E+05
6	1.316E+06	1.095E+06	8.349E+05	4.023E+05	7.561E+05	3.996E+05	4.100E+05	4.127E+05
7	1.336E+06	1.095E+06	7.924E+05	4.023E+05	7.694E+05	3.996E+05	4.107E+05	4.127E+05
8	1.295E+06	1.095E+06	8.265E+05	4.023E+05	7.661E+05	3.996E+05	4.108E+05	4.127E+05
9	1.341E+06	1.095E+06	8.259E+05	4.023E+05	7.565E+05	3.996E+05	4.109E+05	4.127E+05
10	1.300E+06	1.095E+06	8.250E+05	4.023E+05	7.891E+05	3.996E+05	4.105E+05	4.127E+05

In the Table, the output with the best performance is highlighted in bold. It can be found that the maximum value of SIS in the four wave scenarios is significantly higher than that of IDE.

2 Spatial information sampling algorithm

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An intelligent metaphor-free spatial information sampling algorithm for balancing exploitation and exploration

Haichuan Yang [a], Yang Yu [b], Jiujun Cheng [c,*], Zhenyu Lei [a], Zonghui Cai [a], Zihang Zhang [a], Shangce Gao [a,*]

[a] Faculty of Engineering, University of Toyama, Toyama-shi, 930-8555, Japan
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The results of this study are presented in Knowledge-Based Systems.

Spatial information sampling algorithm - Summary

- Although we proposed SIS and obtained higher energy output for the position optimization problems of wave energy converters, SIS did not perform well in solving the wind farm layout optimization problem.

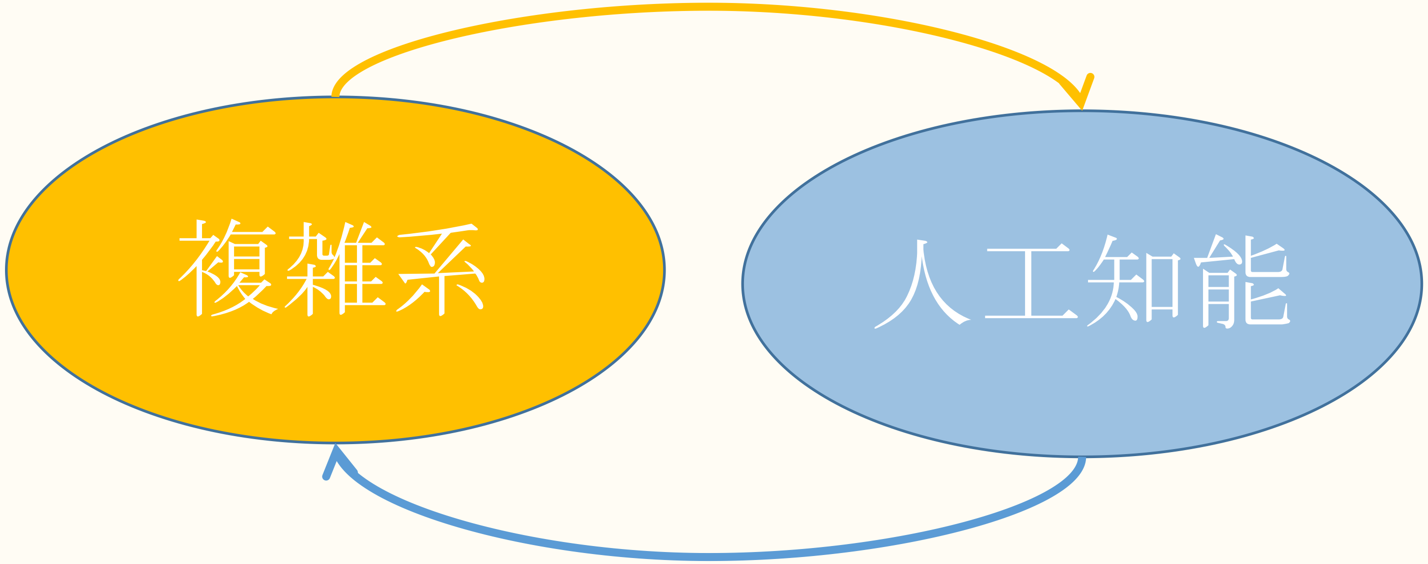
- This shows that relying on exploitation and exploration theory to design the algorithm is not comprehensive, so we introduced complex networks to design the new MHA.

CONTENTS

3 Improved spherical evolution - Complex networks

- The study of large and complex interactions that exist in the real world is known as complex networks. It is also a field of complex systems in that the properties of the entire system are determined by the interaction of numerous factors.

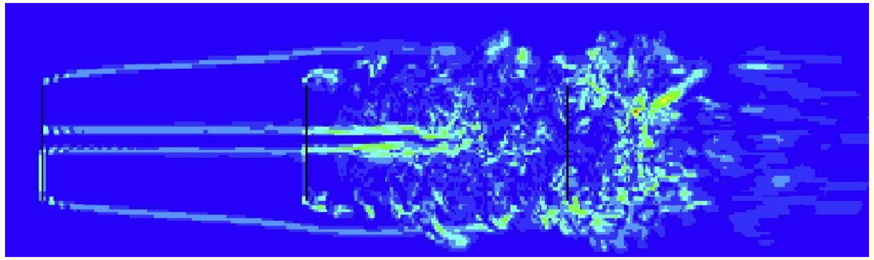
- On the one hand, artificial intelligence can study real complex systems problems. On the other hand, complex systems theory can be used to study artificial intelligence.



3 Improved spherical evolution - Wake effects

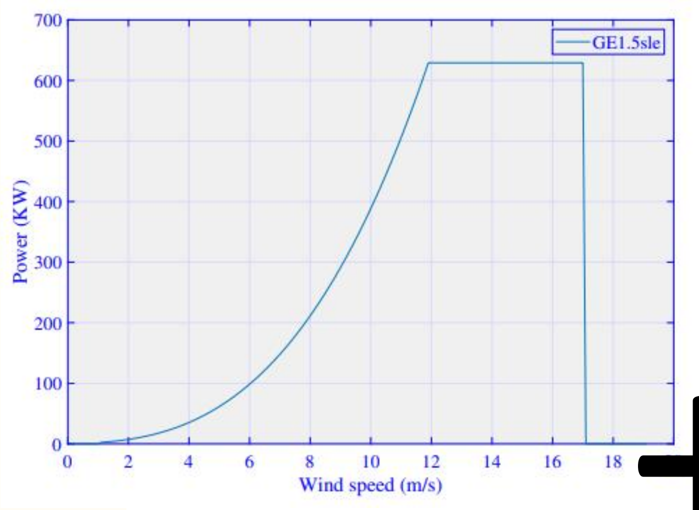
- The optimization problem of wind power generation is one of the NP-complete problems. Since most conventional wind farm layouts follow a certain geometry in a regular manner, the wake effects are also very severe in large wind farms, as shown in the figure.

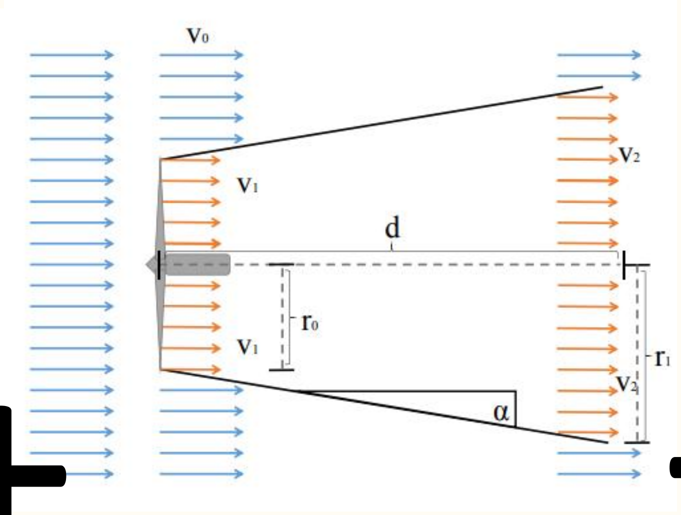
- During the design phase of a wind farm, determining how to construct a rational wind turbine layout that minimizes wake effects is one of the key techniques for increasing the overall power generation capacity of the wind farm.

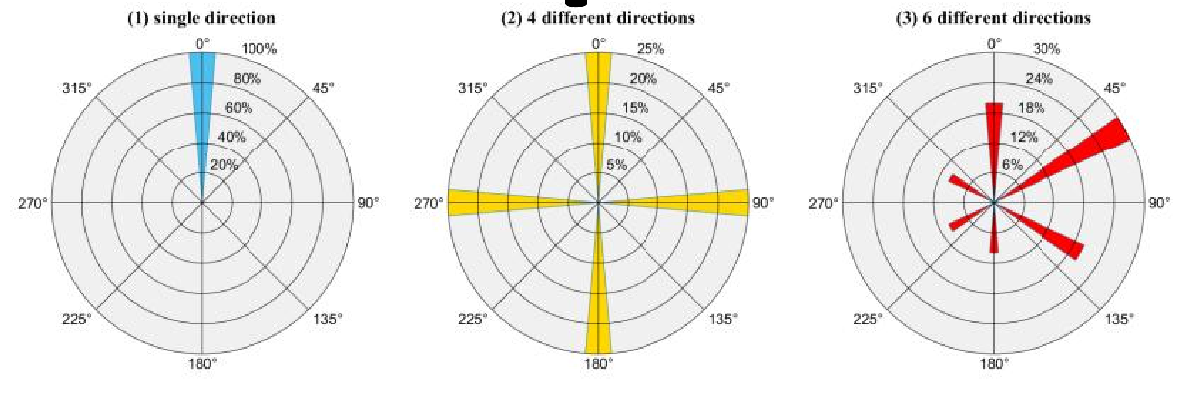


Improved spherical evolution - Construction of wind farm model

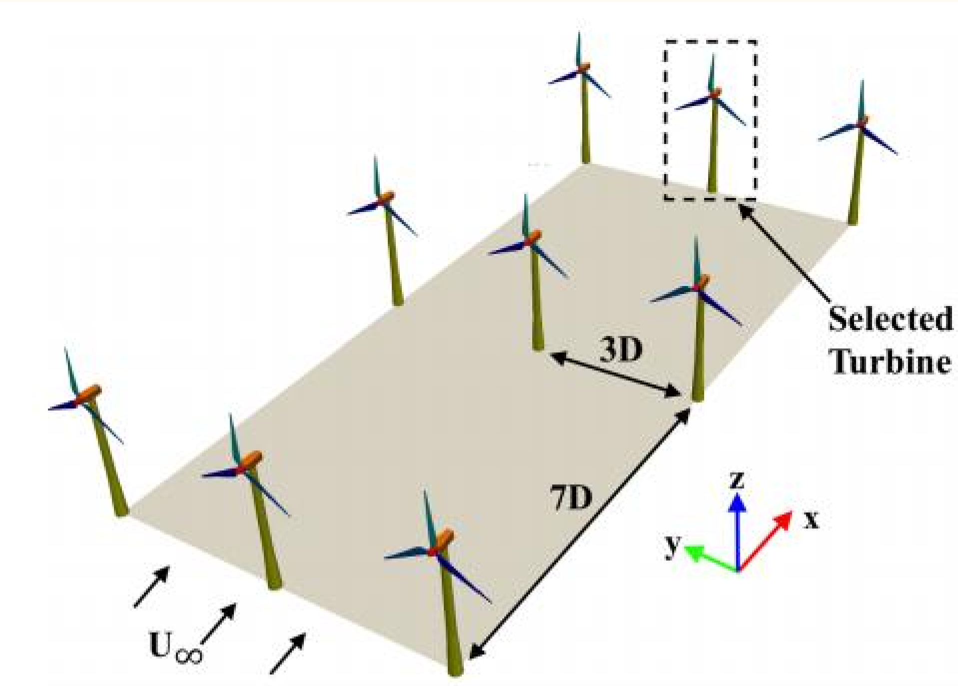
（1）Turbine output model **（2）wake effects model**





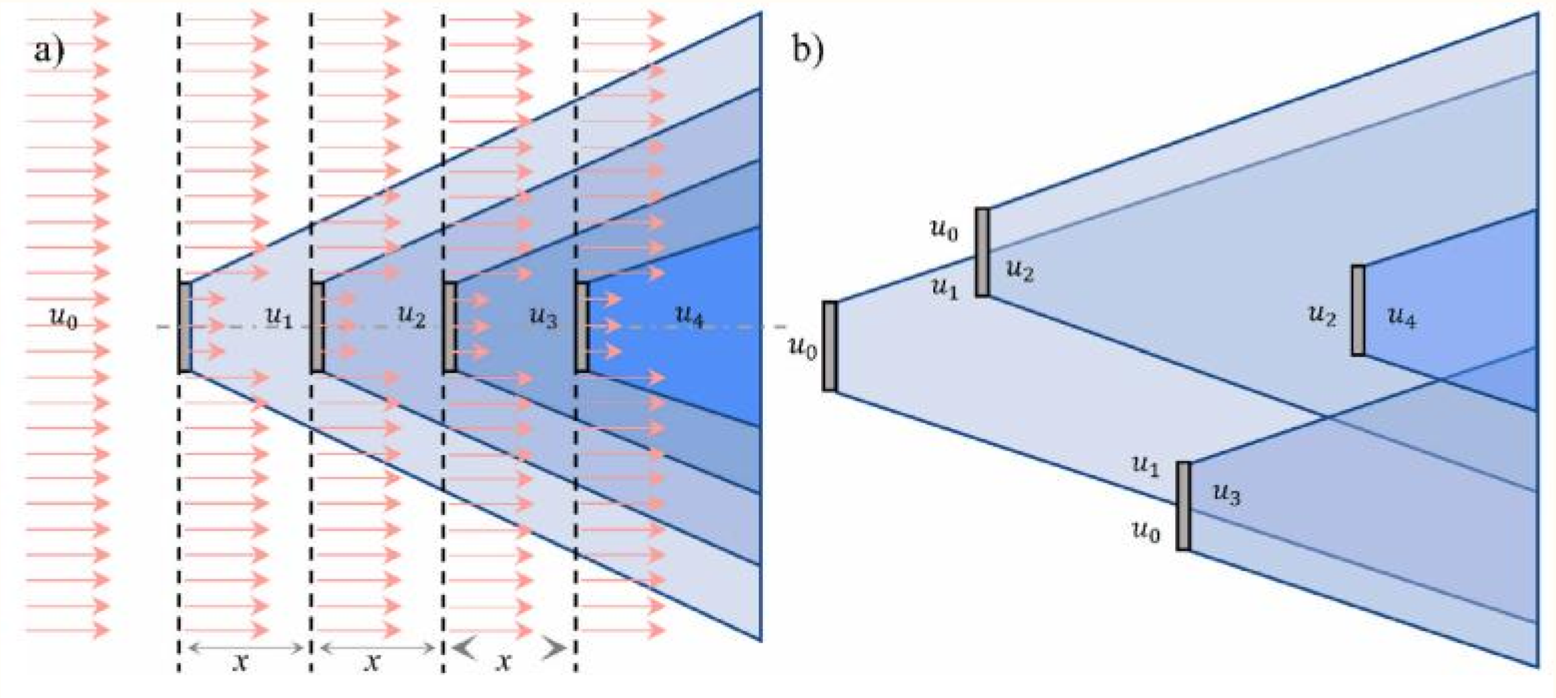


（3）Wind speed and direction model



（4）Wind Farm Model

Top view of wind farm



Objective function = Minimize wake effects (maximize wind energy conversion)

In other words, from the bad situation in Figure a to the ideal situation in Figure b.

3 Improved spherical evolution - Challenges in optimizing the layout of wind farms

Top view of wind farm

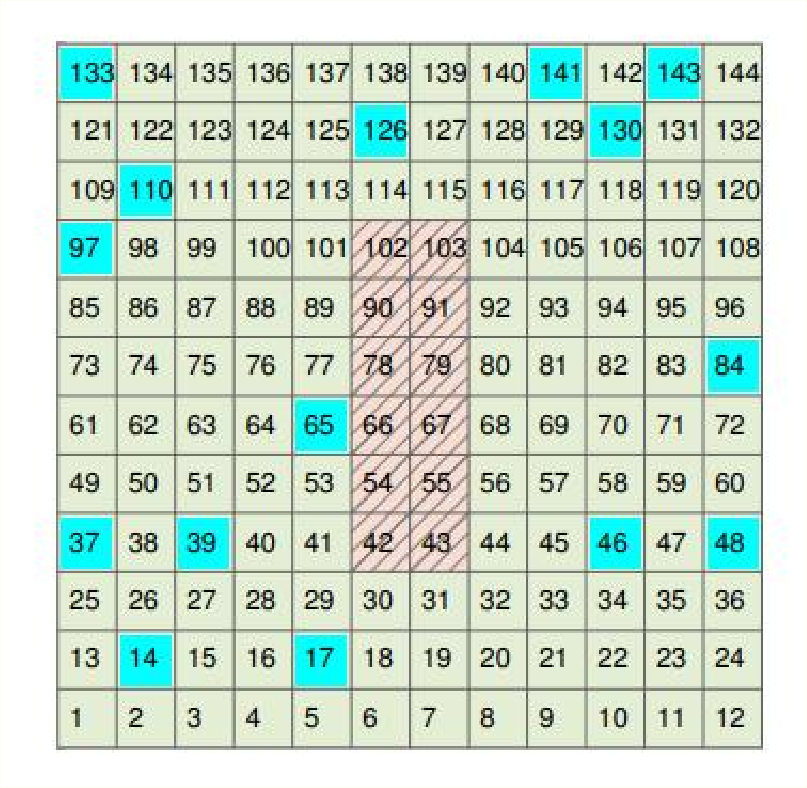
layout solution

- In a layout solution, each square is a location where a wind turbine can be installed. Blue squares are actual wind turbine locations.

- As the size of the wind farm increases, the options for wind turbine placement increase dramatically, making it difficult to choose the option with the lowest wake effects (as shown in the figure on the right).

Top view of large scale wind farm

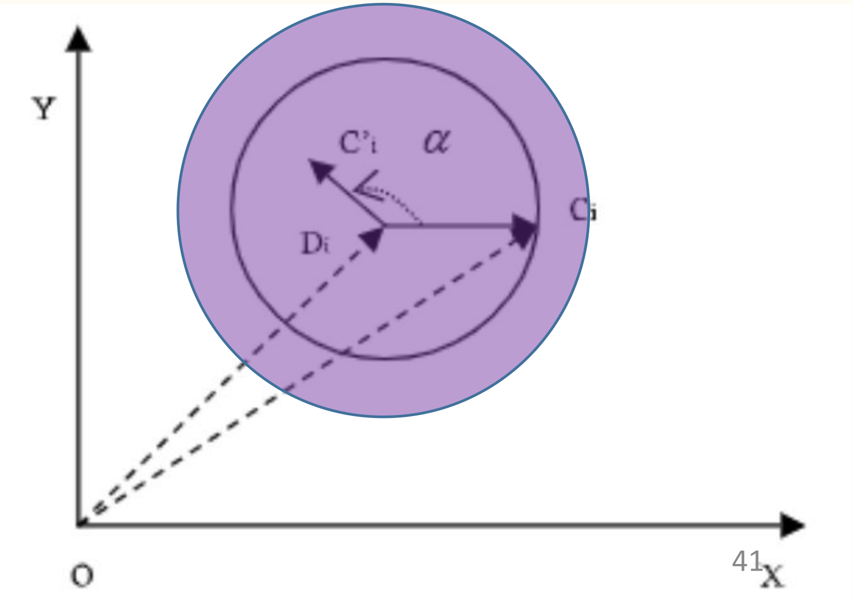
layout solution



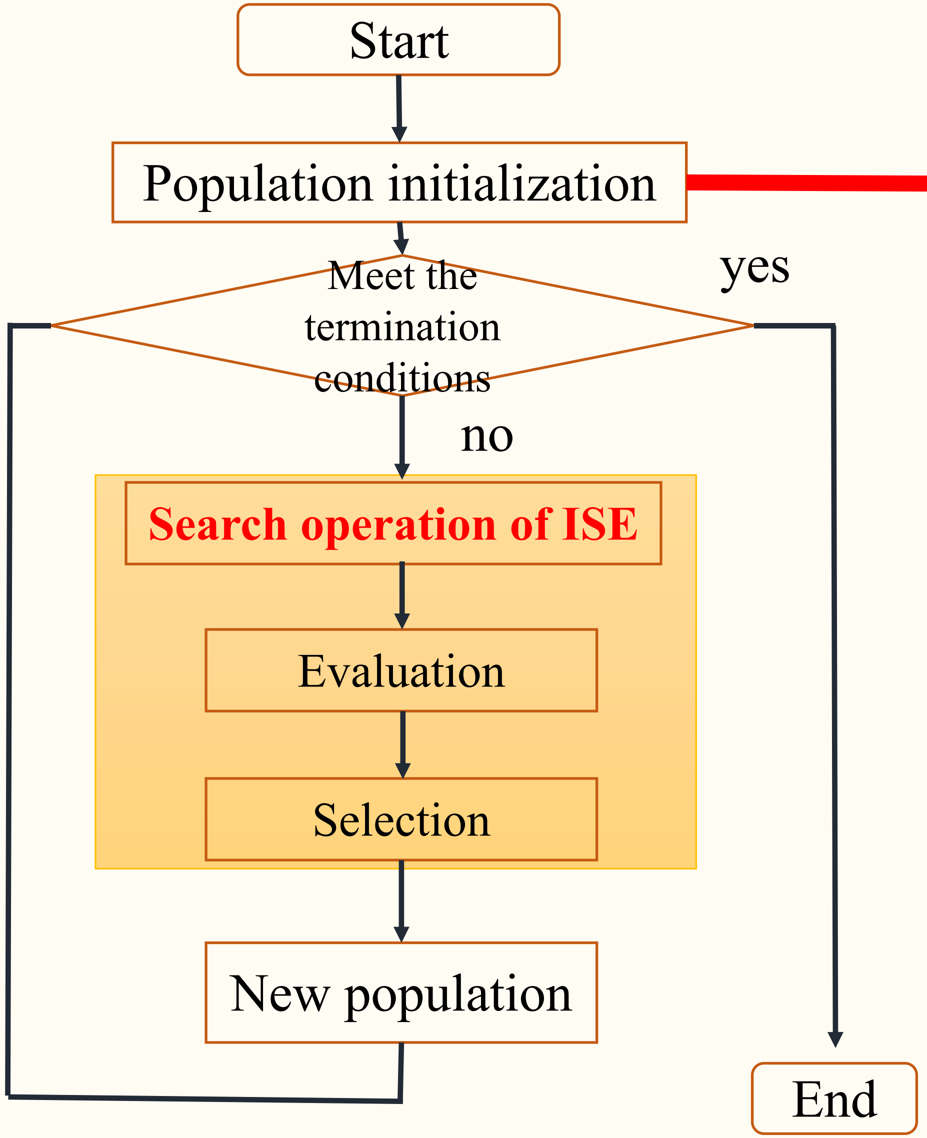
The **search operation of ISE** can be represented as:

$$U_{i,j} = X_{r1,j} + \begin{cases} F \cdot \left\|X_{r2,*} - X_{r3,*}\right\|_2 \cdot \prod_{k=j}^{D_c-1} \sin\left(\theta_j\right), & \text{if } j = 1 \\ F \cdot \left\|X_{r2,*} - X_{r3,*}\right\|_2 \cdot \cos\left(\theta_{j-1}\right) \cdot \prod_{k=j}^{D_c-1} \sin\left(\theta_j\right), & \text{if } 1 < j \leq D_c - 1 \\ F \cdot \left\|X_{r2,*} - X_{r3,*}\right\|_2 \cdot \cos\left(\theta_{j-1}\right), & \text{if } j = D_c \end{cases}$$

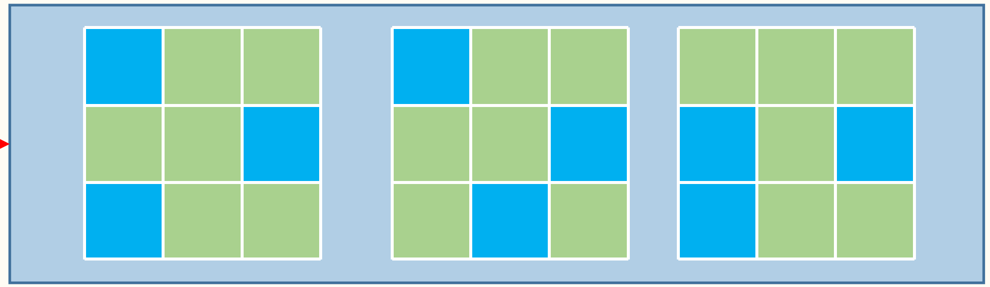
We mainly increased the value of the scaling factor *F*, thus further increasing the search range of SE to try to search for more peaks.



3 Improved spherical evolution - Optimization steps



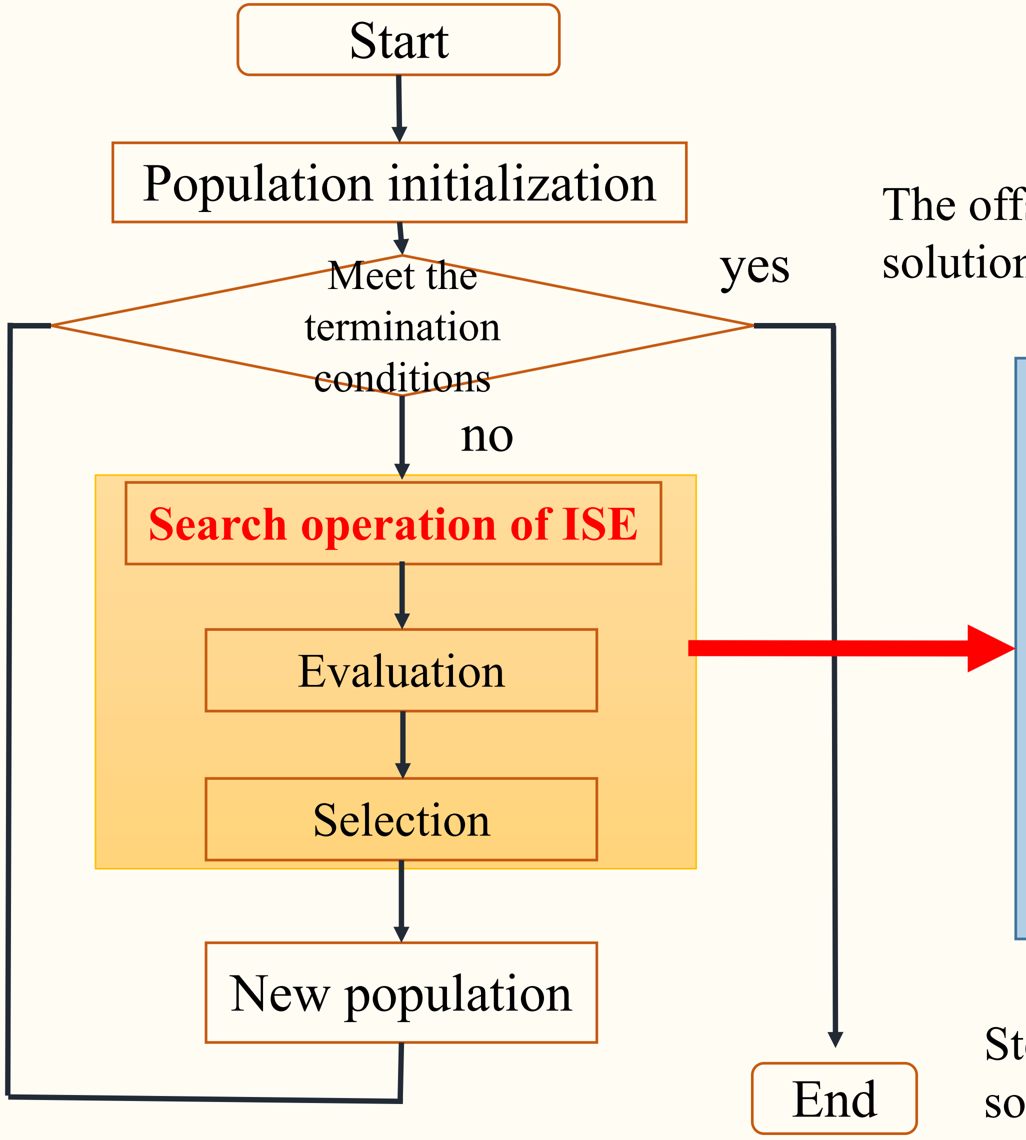
Main steps of ISE



layout solution 1   layout solution 2   layout solution 3

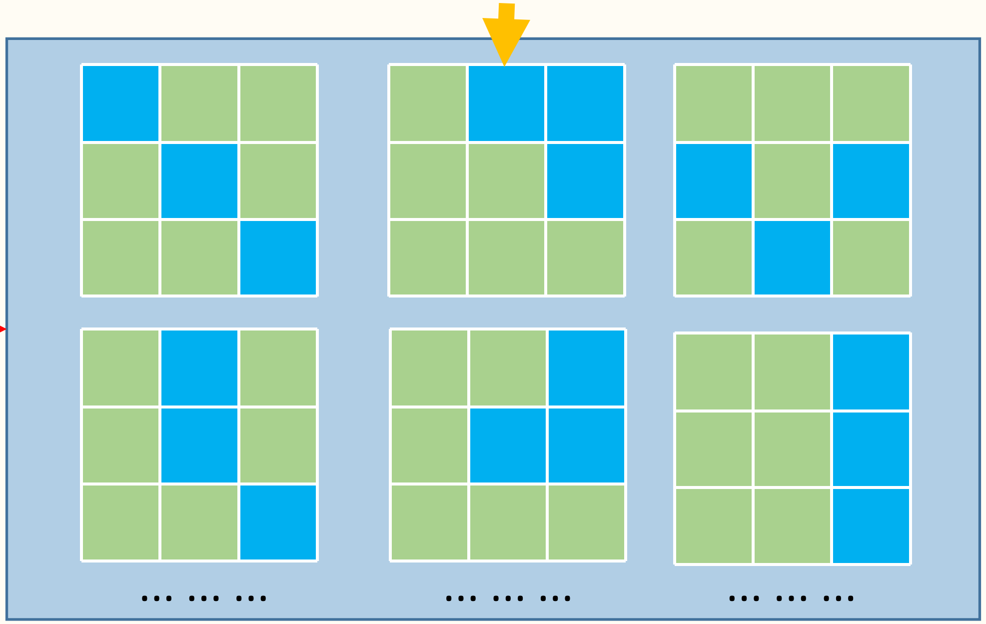
Step 1.First, several parent layout solutions are generated as a population, and the wake effects are calculated for each solution.

Improved spherical evolution - Optimization steps



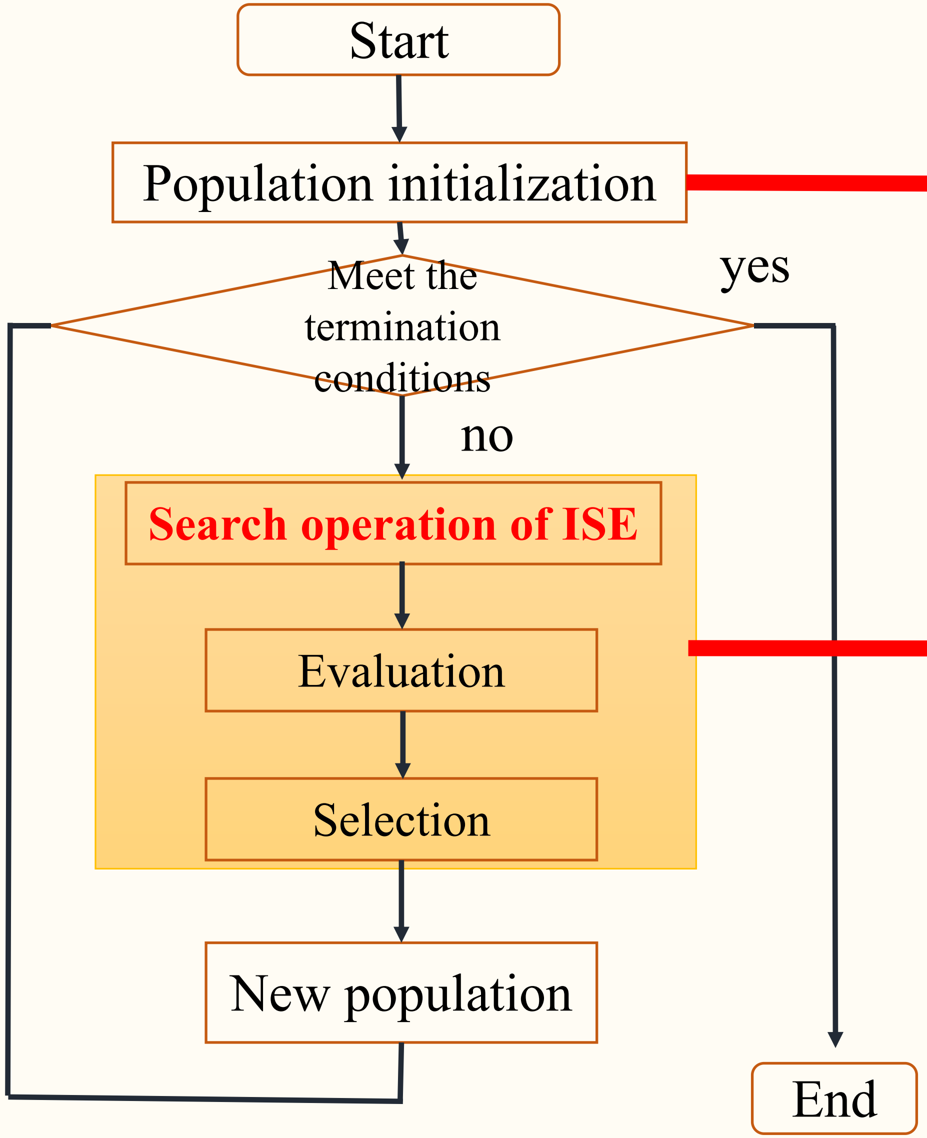
Main steps of ISE

The offspring layout solutions generated by the parent layout solutions.

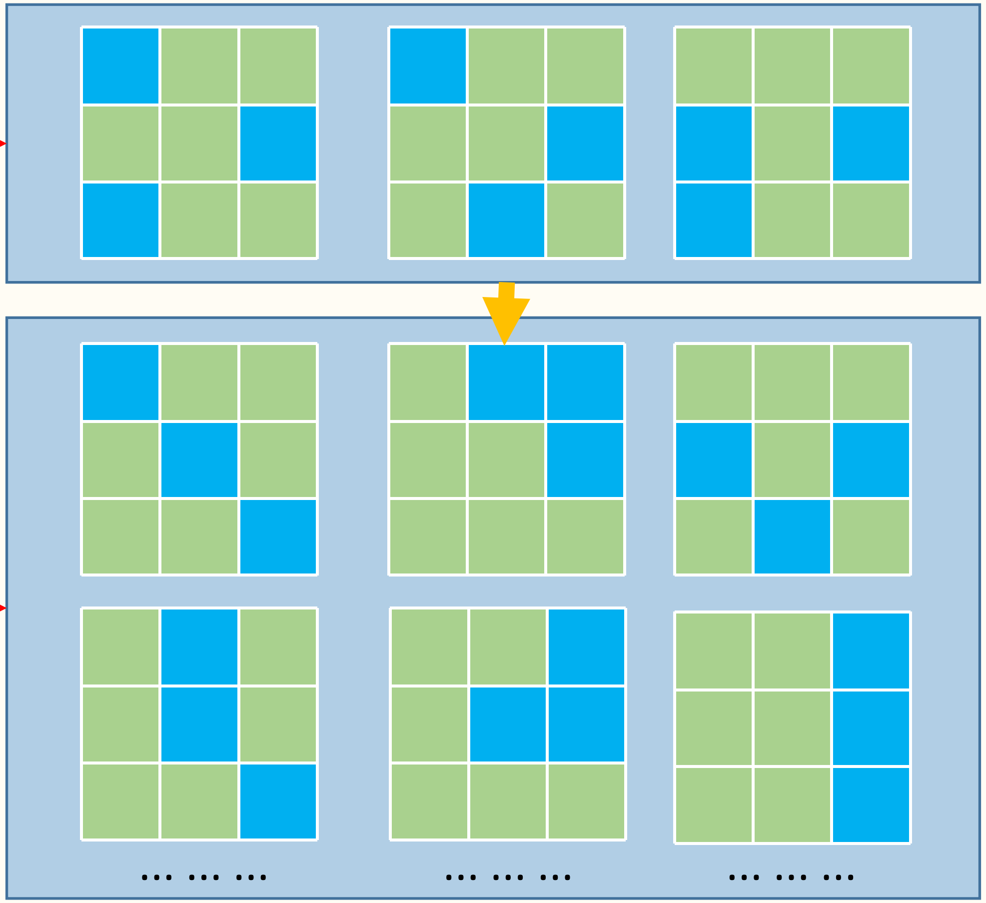


Step 2.Then, a search operation is performed on each layout solutions using ISE to generate new populations.

Improved spherical evolution - Optimization steps

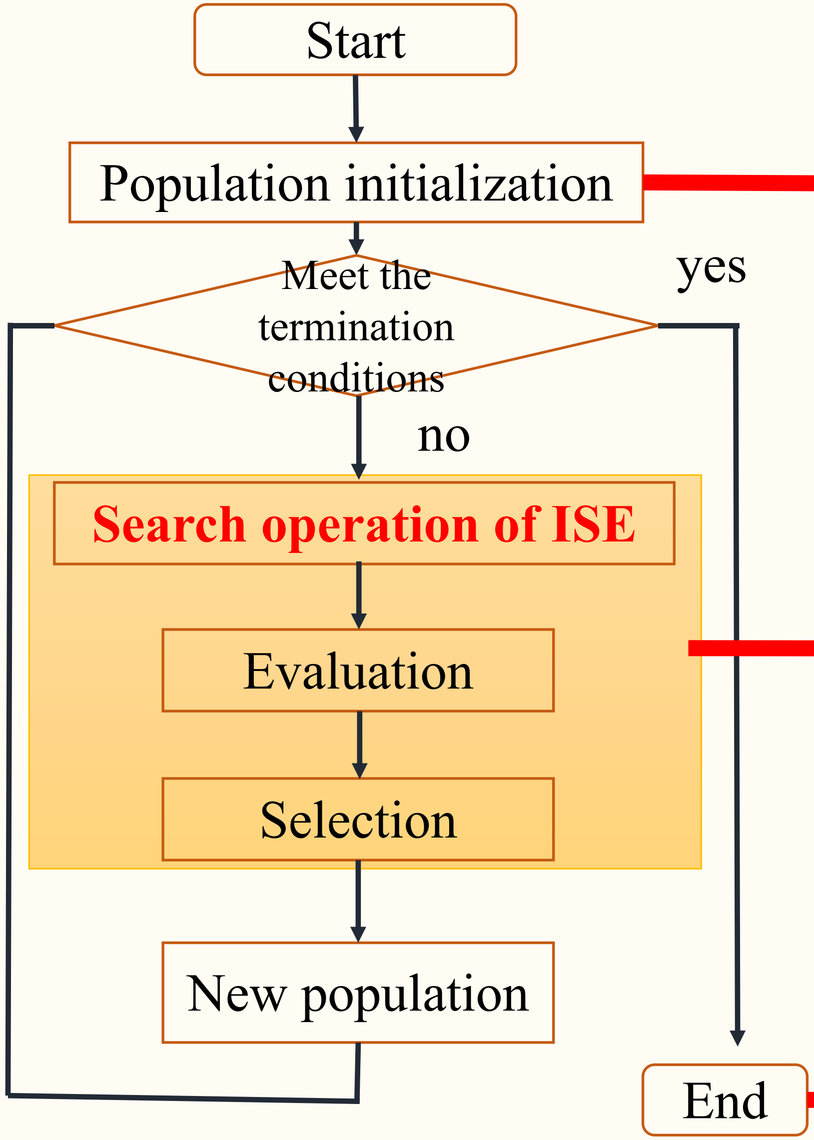


Main steps of ISE

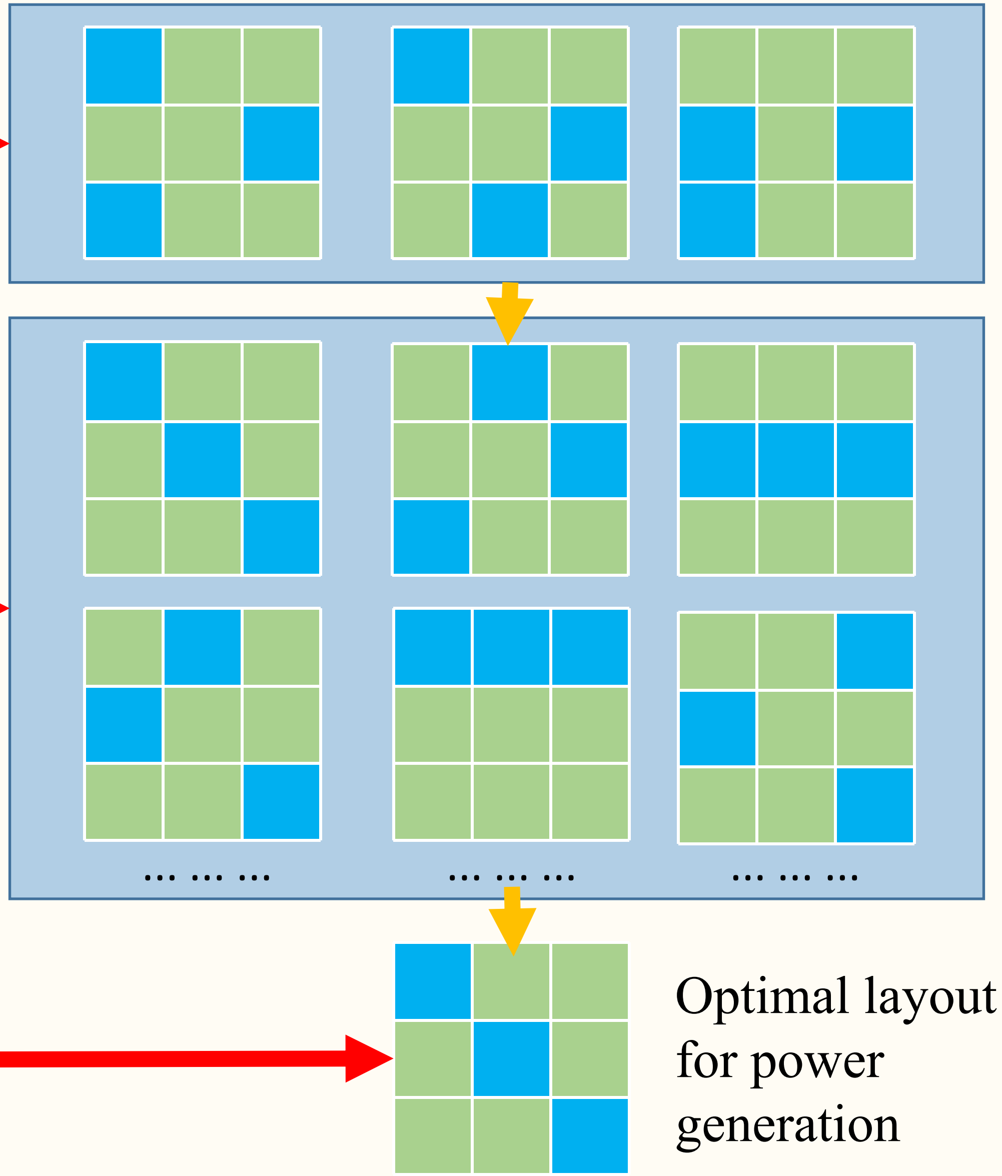


Step 3.The energy conversion rate of each individual (layout solution) in the new population under the influence of the wake effects is calculated by the evaluation operation. The conversion rates of individuals in the new population are then compared with those in the parent population, and the individuals with higher conversion rates are finally selected.

Improved spherical evolution - Optimization steps



Main steps of ISE



After several iterations, the most ideal layout solution is selected.

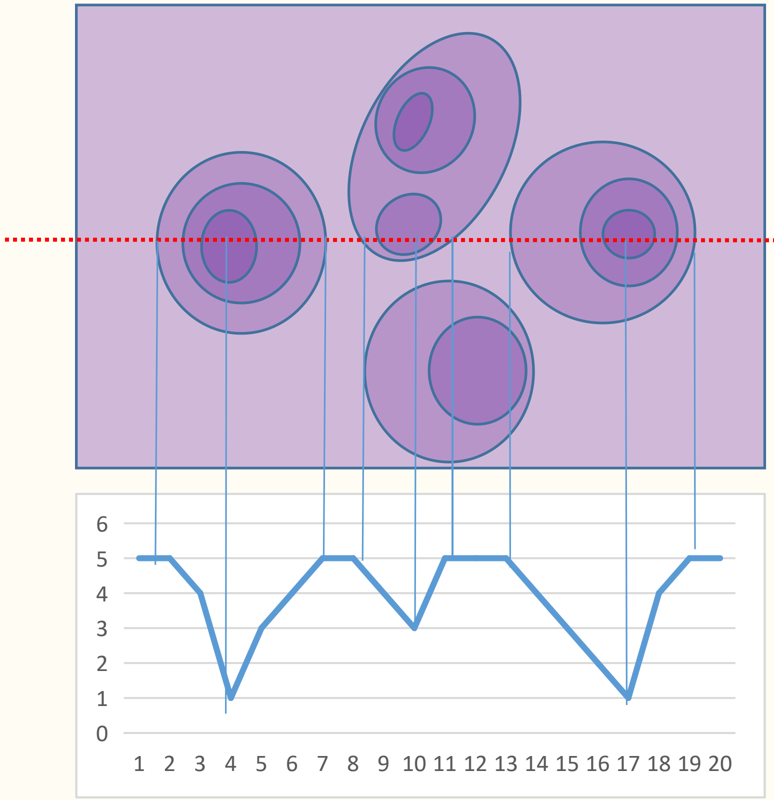
Optimal layout for power generation

3 Improved spherical evolution - Theoretical basis

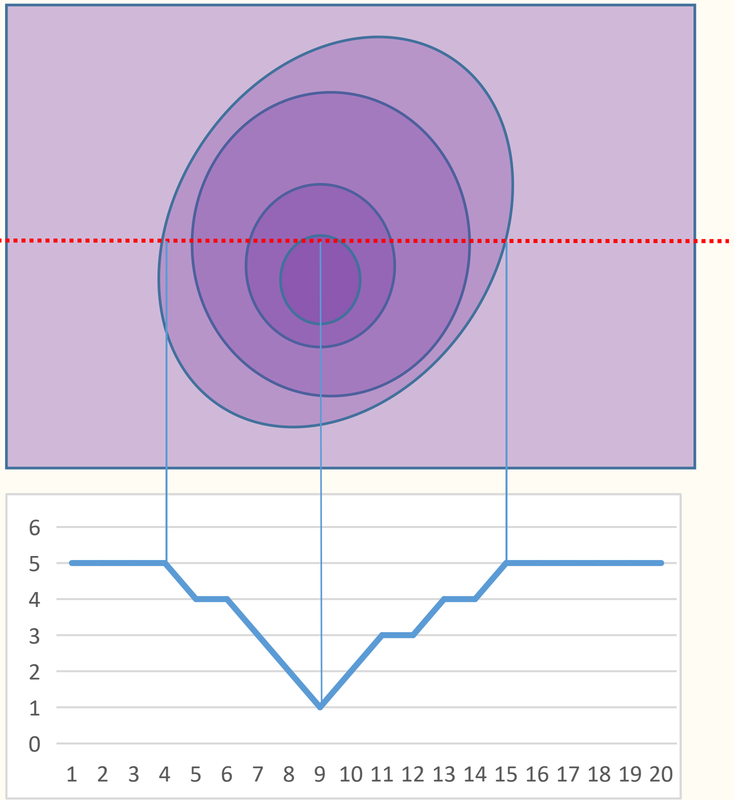
- In the course of our research, we discovered a link between the algorithm and the problem being optimized.

- There are two general types of problems that are optimized: multi-peak problems and single-peak problems.

multi-peak problems

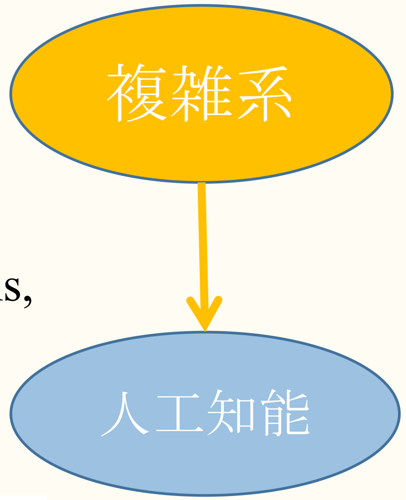


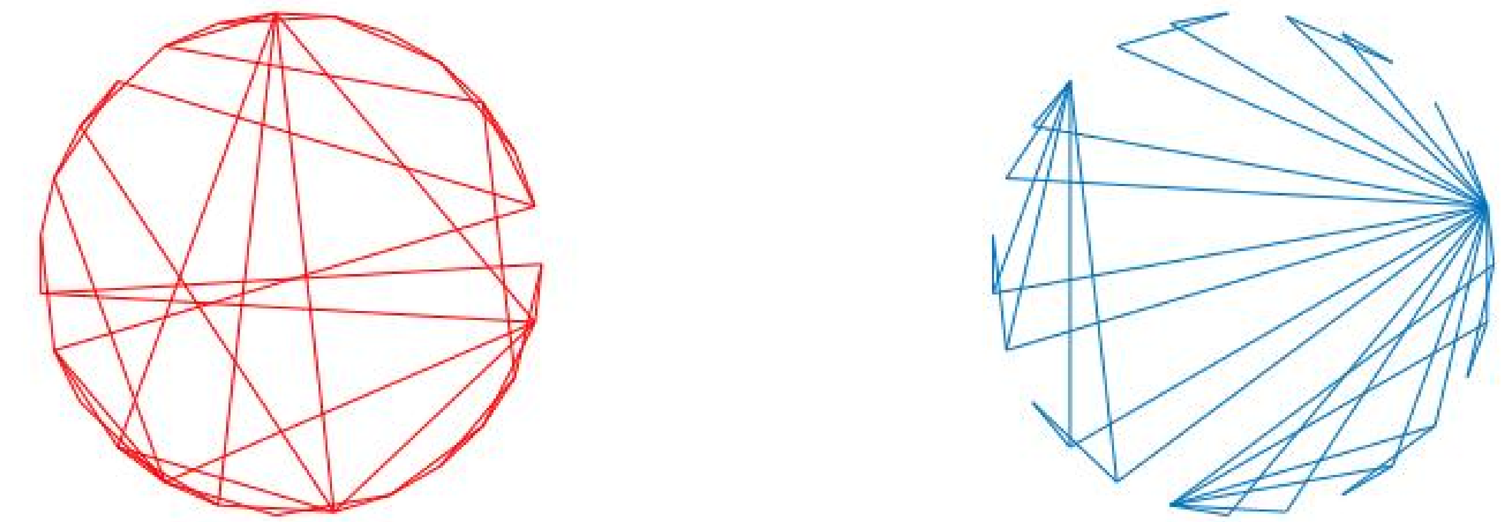
single-peak problems



3 Improved spherical evolution - Theoretical basis

- Interestingly, MHAs fall into two categories depending on the complexity of the network.
- We count the links between individuals during the iterations of the algorithm and fit the obtained data.
- Eventually, it is determined that some MHAs are small-world networks with Poisson distributions, while others are scale-free networks.





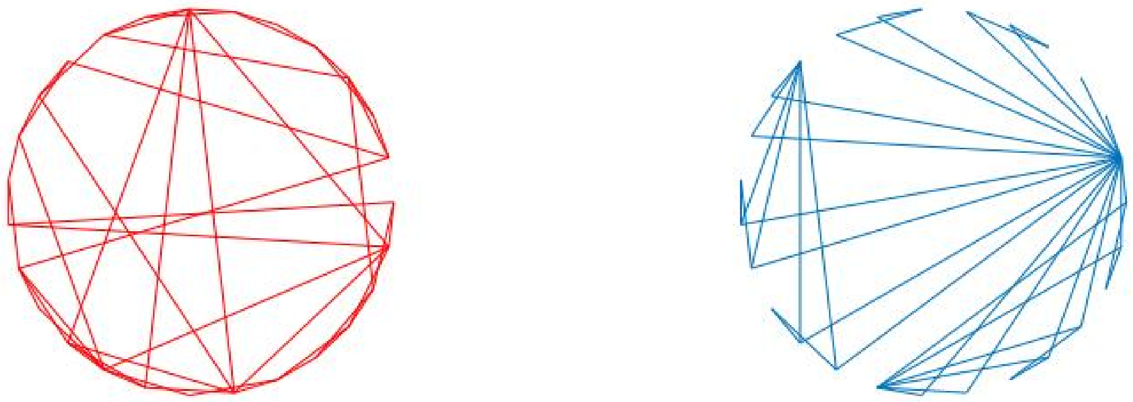
(a) Complex networks with Poisson degree distribution.

(b) Complex networks with power-law (i.e., scale-free) degree distribution.

3 Improved spherical evolution - Theoretical basis

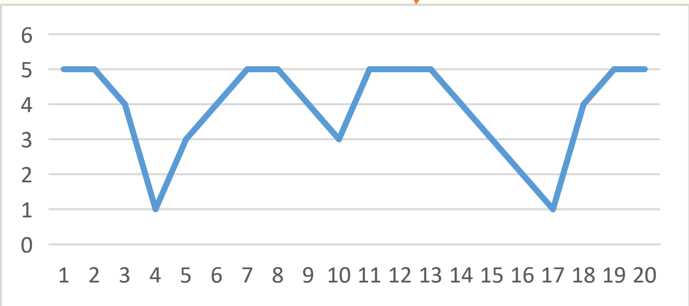
- MHAs with small-world network properties are suitable for optimizing multi-peak problems, while algorithms with scale-free network properties are suitable for optimizing single-peak problem.

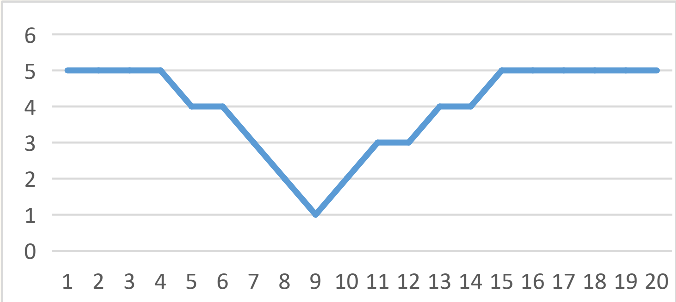
- Based on this finding, researchers can quickly select the corresponding metaheuristic algorithms for problems with different characteristics, thus greatly reducing the trial-and-error cost.



(a) Complex networks with Poisson degree distribution.

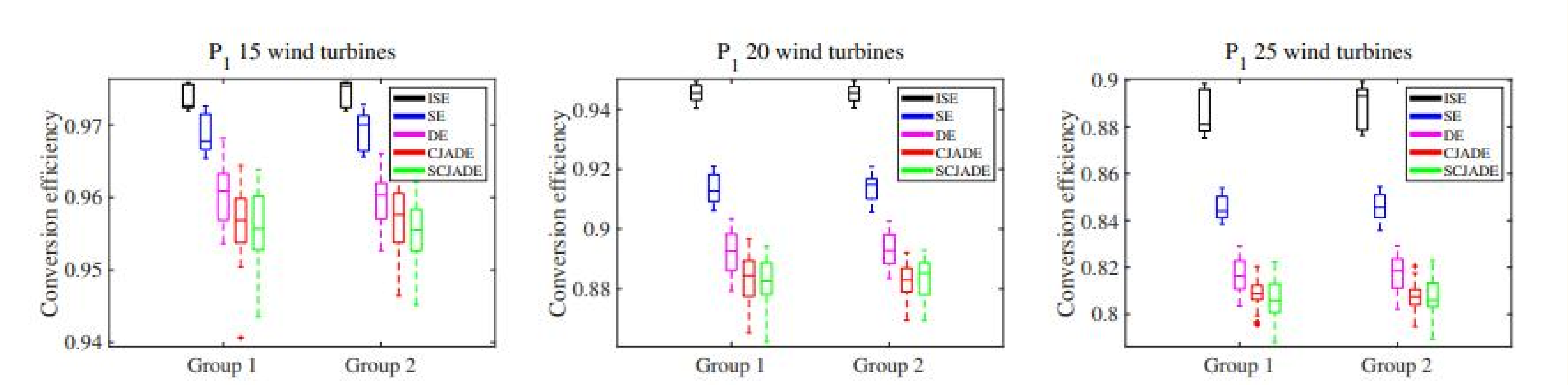
(b) Complex networks with power-law (i.e., scale-free) degree distribution.





Improved spherical evolution - Theoretical basis

- Experimental results show that SE [15] and DE [16] algorithms with small-world network properties are superior to CJADE [17] and SCJADE [18] with scale-free network properties on WFLOP.
- We speculate that WFLOP is more oriented to multi-peak problems and therefore propose the improved SE.



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17.Gao, S., Yu, Y., Wang, Y., Wang, J., Cheng, J., & Zhou, M. (2019). Chaotic local search-based differential evolution algorithms for optimization. IEEE Transactions on Systems, Man, and Cybernetics: Systems, 51(6), 3954-3967.
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Improved spherical evolution - Experimental Results

- Experimental results show that the ISE is superior to SE, DE, CJADE and SCJADE on WFLOP.

	ISE	SE	DE	SCJADE	CJADE
Score	5	4	2.3419	2.1197	1.5385
Rank	1	2	3	4	5

Friedman test of five algorithms on WFLOP.

Table 4: Efficiency performance comparison under wind profile P_1.

	ISE		SE			DE			CJADE			SCJADE		
$P_1(15)$	mean	std	mean	std		mean	std		mean	std		mean	std	
L0	9.788E-01	4.199E-04	9.759E-01	1.194E-03	+	9.727E-01	1.988E-03	+	9.686E-01	2.971E-03	+	9.700E-01	3.188E-03	+
L1	9.696E-01	1.121E-16	9.664E-01	1.440E-03	+	9.634E-01	2.382E-03	+	9.584E-01	3.619E-03	+	9.603E-01	3.431E-03	+
L2	9.789E-01	1.958E-04	9.771E-01	9.454E-04	+	9.753E-01	1.270E-03	+	9.748E-01	2.265E-03	+	9.747E-01	1.921E-03	+
L3	9.641E-01	1.022E-03	9.528E-01	2.732E-03	+	9.488E-01	3.427E-03	+	9.456E-01	4.377E-03	+	9.462E-01	4.595E-03	+
L4	9.642E-01	9.380E-04	9.522E-01	2.324E-03	+	9.474E-01	3.329E-03	+	9.444E-01	4.437E-03	+	9.443E-01	4.932E-03	+
L5	9.789E-01	1.958E-04	9.774E-01	8.578E-04	+	9.766E-01	1.435E-03	+	9.757E-01	1.441E-03	+	9.759E-01	1.685E-03	+
L6	9.788E-01	3.322E-04	9.739E-01	1.611E-03	+	9.671E-01	3.077E-03	+	9.618E-01	5.131E-03	+	9.608E-01	4.633E-03	+
L7	9.747E-01	2.376E-04	9.716E-01	1.486E-03	+	9.679E-01	2.621E-03	+	9.650E-01	3.473E-03	+	9.639E-01	3.536E-03	+
L8	9.789E-01	2.371E-16	9.766E-01	1.219E-03	+	9.747E-01	1.850E-03	+	9.723E-01	2.819E-03	+	9.730E-01	2.082E-03	+
L9	9.716E-01	6.066E-04	9.649E-01	1.996E-03	+	9.610E-01	2.516E-03	+	9.584E-01	3.698E-03	+	9.573E-01	3.834E-03	+
L10	9.715E-01	6.759E-04	9.651E-01	1.850E-03	+	9.617E-01	2.747E-03	+	9.574E-01	4.263E-03	+	9.582E-01	5.165E-03	+
L11	9.789E-01	1.360E-16	9.768E-01	1.159E-03	+	9.752E-01	1.547E-03	+	9.733E-01	2.303E-03	+	9.736E-01	2.426E-03	+
L12	9.788E-01	5.045E-04	9.735E-01	1.394E-03	+	9.689E-01	2.843E-03	+	9.645E-01	3.563E-03	+	9.636E-01	3.789E-03	+
W/T/L	-/-/-		13/0/0			13/0/0			13/0/0			13/0/0		

Conversion efficiency on wind distribution P1

ISE is also found to be significantly better than the SUGGA and LSHADE (Top algorithms in the field of MHAs) .

Table 8: Comparison between ISE, SUGGA, and LSHADE under wind profile P_1.

$P_1(15)$	ISE		SUGGA			LSHADE		
	mean	std	mean	std		mean	std	
L0	9.788E-01	4.199E-04	9.775E-01	1.110E-15	+	9.782E-01	9.005E-04	+
L1	9.696E-01	1.121E-16	9.730E-01	1.221E-15	-	9.693E-01	8.710E-04	+
L2	9.789E-01	1.958E-04	9.775E-01	1.110E-15	+	9.789E-01	5.571E-16	=
L3	9.641E-01	1.022E-03	9.719E-01	6.661E-16	-	9.595E-01	1.771E-03	+
L4	9.642E-01	9.380E-04	9.789E-01	5.551E-16	-	9.599E-01	2.091E-03	+
L5	9.789E-01	1.958E-04	9.789E-01	5.551E-16	=	9.788E-01	2.741E-04	=
L6	9.788E-01	3.322E-04	9.775E-01	1.110E-15	+	9.762E-01	1.731E-03	+
L7	9.747E-01	2.376E-04	9.761E-01	8.882E-16	-	9.740E-01	9.703E-04	+
L8	9.789E-01	2.371E-16	9.789E-01	5.551E-16	=	9.787E-01	4.859E-04	+
L9	9.716E-01	6.066E-04	9.691E-01	1.110E-15	+	9.697E-01	1.133E-03	+
L10	9.715E-01	6.759E-04	9.775E-01	1.110E-15	-	9.688E-01	2.672E-03	+
L11	9.789E-01	1.360E-16	9.789E-01	5.551E-16	+	9.788E-01	4.199E-04	+
L12	9.788E-01	5.045E-04	9.775E-01	1.110E-15	+	9.764E-01	1.007E-03	+
W/T/L	-/-/-		6/2/5			11/2/0		
p-value	-		8.529E-01			1.328E-03		

CONTENTS

Conclusion

Purpose

- In this study, we design a SIS algorithm and an ISE algorithm to address WEC and WFLOP, respectively.

Method

- The design of SIS and ISE is based on exploitation and exploration theory and complex network theory.

Significance

- The development of the above two algorithms not only effectively improves the conversion efficiency of renewable energy, but also lays the foundation for further application of MHAs in the field of energy optimization.

THANK YOU