*Supplementary materials

1. The advantages of GWO

GWO is a swarm intelligence optimization algorithm proposed by Mirjalili et.al in 2014. It is inspired from the strict social hierarchy and hunting activities of the grey wolves. The advantages of GWO are as follows:

a) Simple structure makes the GWO easier to simulated and developed.
b) It can be applied to solve different complex problems without changing the structure of the algorithm.
c) It can excellently prevent the optimal solution from falling into local optimization. And it has derivation-free mechanisms which can be effectively used for solving the problems for which objective functions are inconsistency, or even discontinuous. It highly suitable for solving nonlinear, multivariable optimization problem.

2. The mathematical model of GWO

2.1 Social hierarchy

Gray wolves prefer to live in groups, with a strict hierarchy within them. While modelling and simulating the occurrence of gray wolves, the social hierarchy need to be constructed in the first time. The fittest solution is considered as alpha wolf (α), and the second and third fitness solution are considered as beta wolf (β) and delta wolf (δ) respectively. The lowest grade is omega wolf (ω), which mainly serves for high-level gray wolves. The α is responsible for tracking the prey and making decision whether to hunt or not. As β respect α and help α to make a decision. The rest δ obey the instructions of α and β, and also can dominate the wolves of the lowest grade.

2.2 Encircling the prey

The strict hierarchy provides an institutional guarantee for the hunting activities of gray wolves. The hunting activities of the gray wolves mainly include: tracking, encircling, and attacking. The main mathematical model as shown in the Eq.1-Eq.3.

$$D_{mn} = | C_m(t) \times X^P_{mn}(t) - X_{mn}(t) | \quad (1)$$

$$X_{mn}(t+1) = X^P_{mn}(t) - A_m(t) \times D_m(t) \quad (2)$$

$$A_m(t) = 2 \times a_m(t) \times r_{m1} - a_m(t), \quad C_m(t) = 2 \times r_{m2} \quad (3)$$

Where t is the number of the iteration, X^P_{mn} represents the position vector of the prey, and X_{mn} represents the position vector of a grey wolf. $a_m(t)$ are reduced from 2 to 0 in accordance with the iterations during the whole iteration process, and r_{m1}, r_{m2} are random vectors in [0,1].

2.3 Hunting the prey

The hunting of gray wolves is also called as optimization in the mathematical model. Find the best overall best point (prey) through continuous optimization. Through each iteration, the positions of the best three gray wolves in the current population are retained, and then the positions of other search agents (including ω) are updated according to their position information. The main mathematical model as shown in the Eq.4.

$$D^\alpha_{mn} = | C^1_m \times X^\alpha_{mn} - X_{mn} |; \; D^\beta_{mn} = | C^2_m \times X^\beta_{mn} - X_{mn} |; \; D^\delta_{mn} = | C^3_m \times X^\delta_{mn} - X_{mn} |;$$

$$X^1_{mn} = X^\alpha_{mn} - A^1_m \times D^\alpha_{mn}; \; X^2_{mn} = X^\beta_{mn} - A^2_m \times D^\beta_{mn}; \; X^3_{mn} = X^\delta_{mn} - A^3_m \times D^\delta_{mn};$$

$$X_{mn}(t+1) = \frac{X^1_{mn} + X^2_{mn} + X^3_{mn}}{3} \quad (4)$$

Where X^α_{mn}, X^β_{mn}, X^δ_{mn} represents the position vector of α, β, δ respectively. X_{mn} represent the position vector of grey wolves. D^α_{mn}, D^β_{mn}, D^δ_{mn} represents the distance between the current candidate gray wolf and the best three wolves respectively.

Over the course of iterations, alpha, beta, and delta wolves estimate the probable position of the prey. The candidate solution updates its distance from the prey. During the process of search for prey, gray wolves mainly rely on the α, β, δ wolves to find the prey, the search rule is to disperse in the first time, and then focus on attacking the prey. The main step is to balance the process of search for prey and attacking prey. The algorithm use |A|>1 to keep the searching agent away from the prey. With using this step enables GWO to perform a global search. Another search coefficient in the GWO algorithm is C. According to the Eq.3, it can be seen that the C vector is a vector composed of random values in the interval [0, 2]. This coefficient provides a random weight for the prey. This helps GWO to exhibit random search behaviour in the optimization process, so as to avoid the algorithm from falling into the local optimum.

In the process of attacking the prey, A is a random vector in the interval [-a, a]. When A belongs to the interval [-1, 1], the next time position of the search agent can be anywhere between the current gray wolf and the prey. Search for prey and attacking prey are guaranteed by the adaptive values of a and A. With decreasing A, half of the iterations are devoted to search for prey and the other half are dedicated to attacking prey. Finally, the GWO algorithm is terminated by the satisfaction of an end criterion.