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Task Allocation of Multi-Machine Collaborative Operation for Agricultural Machinery Based on the Improved Fireworks Algorithm

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Abstract: Currently, the multi-machine collaboration of agricultural machinery is one of the international frontiers and a topic of research interest in the field of agricultural equipment. However, the multi-machine cooperative operation of agricultural machinery is mostly limited to the research on task goal planning and cooperative path optimization of a single operation. To address the mentioned shortcomings, this study addresses the problem of multi-machine cooperative operation of fertilizer applicators in fields with different fertility and fertilizer cooperative distribution of fertilizer trucks. The research uses the task allocation method of a multi-machine cooperative operation of applying fertilizer-transporting fertilizer. First, the problems of fertilizer applicator operation and fertilizer truck fertilizer distribution are defined, and the operating time and the distribution distance are used as optimization objectives to construct functions to establish task allocation mathematical models. Second, a Chaos–Cauchy Fireworks Algorithm (CCFWA), which includes a discretized decoding method, a population initialization with a chaotic map, and a Cauchy mutation operation, is developed. Finally, the proposed algorithm is verified by tests in an actual scenario of fertilizer being applied in the test area of Jimo District, Qingdao City, Shandong Province. The results show that compared to the Fireworks Algorithm, Genetic Algorithm, and Particle Swarm Optimization, the proposed CCFWA can address the problem of falling into a local optimum while guaranteeing the convergence speed. Also, the variance of the CCFWA is reduced by more than 48% compared with the other three algorithms. The proposed method can realize multi-machine cooperative operation and precise distribution of seeds and fertilizers for multiple seeding-fertilizer applicators and fertilizer trucks.

Keywords: agricultural machinery; multi-machine collaboration; task allocation; the fireworks algorithm; chaotic map; Cauchy mutation

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1. Introduction

Currently, multi-machine collaboration of agricultural machinery is one of the main research topics in the field of agricultural machinery and, thus, has attracted much attention internationally. Reasonably arranging the cooperative operation of multiple agricultural machinery or multiple types of agricultural machinery, that is, realizing a multi-machine cooperative operation of agricultural machinery, can be an important way to reduce the cost and increase the efficiency of agricultural machinery [1–3].

The existing research on the multi-machine cooperative problem of agricultural machinery mainly addresses two aspects: path planning [4,5] and task allocation [6,7]. Cao et al. used time windows to detect different types of conflicts after planning the path to address the problem of path conflicts in multi-machine cooperative path planning of agricultural machinery [8]. Shi et al. used unmanned aerial vehicles (UAVs) to collect field information, which was then used to detect field obstacles and assist agricultural machinery in avoiding field obstacles [9]. Zhai et al. performed path planning for master-slave agricultural machinery, where the paths for slave operations were formulated based on the relative distances of the master and slave and the turning states to avoid collisions [10]. Jiang et al. proposed an adaptive immune following algorithm based on the immune algorithm and artificial fish swarm algorithm to assign fields with a different amount of work to the agricultural machinery group [11]. Wang et al. divided the path planning methods between the fields into several categories according to the positional relationship between the fields and assigned the fields to the agricultural machinery group accordingly [12,13]. Gong et al. divided a field into multiple areas according to the obstacles in the field and then allocated these areas to the agricultural machinery group [14]. However, the aforementioned studies have mainly focused on the collaboration of the agricultural machinery group and multi-machine cooperative algorithms [15,16].

Unlike the literature mentioned above, this study investigates the problem of multi-machine cooperative operation, where multiple fertilizer applicators apply fertilizer to fertility fields and fertilizer trucks work together to transport the fertilizer. The size and fertility of different fields are different [17–19]; the lower the fertility of the field, the greater the amount of applied fertilizer and the lower the speed of the fertilizer applicator will be. Also, fertilizers are distributed by a fertilizer truck on time to the corresponding turnrow according to the operating process of fertilizer applicators, causing the cooperative problem of various agricultural machinery and different types of agricultural machinery. This type of problem involves many factors and has a complex model, so establishing an optimization model of the multi-machine cooperative operation of applying fertilizer-transporting fertilizer, as well as designing the corresponding algorithms with strong solving ability, has been the main challenge.

Aiming at the above problem, this study considers the actual operation mode and fertilizer distribution mode comprehensively to sort out the cooperative problem and constructs the objective functions with the operating time of fertilizer applicators and the distribution distance of the fertilizer truck as optimization objectives. In addition, an improved fireworks algorithm is proposed to solve the task allocation problem of fertilizer applicators and fertilizer distribution of the fertilizer truck.

2. Materials and Methods

2.1. Problem Description

2.1.1. Task Allocation of Multi-Machine Cooperative Operation of Fertilizer Applicators

(1) Characteristics of fertilizer applicator operation scenario

Common full-coverage operation methods for agricultural machinery include reciprocating and spiral methods, but the reciprocating method provides more coverage in comparison. Consider a field T_j, which is a rectangular field with four vertex coordinates denoted as (x_{Tj1}, y_{Tj1}), (x_{Tj2}, y_{Tj2}), (x_{Tj3}, y_{Tj3}), and (x_{Tj4}, y_{Tj4}), as shown in Figure 1. The fertilizer applicator enters from a certain vertex, performs the reciprocating operation, and then, after operating the current column, turns around to operate the next column until the field is fully operated. The length of each column is l_{Tj}, and the field width is d_{Tj}.

(2) Description of task allocation problem of fertilizer applicators

Multiple fields require fertilizer application, and the agricultural cooperative has many fertilizer applicators that can be used for applying fertilizer. The fields are assigned to different fertilizer applicators, and their operation sequences are predefined. As shown in Figure 2, there are 10 fields in total. The operation route of a certain fertilizer applicator to complete the assigned fields is garage→1→2→7→3→5→garage. The fertilizer applicator operates in a reciprocating method on the field, as shown in field 5 in Figure 2.

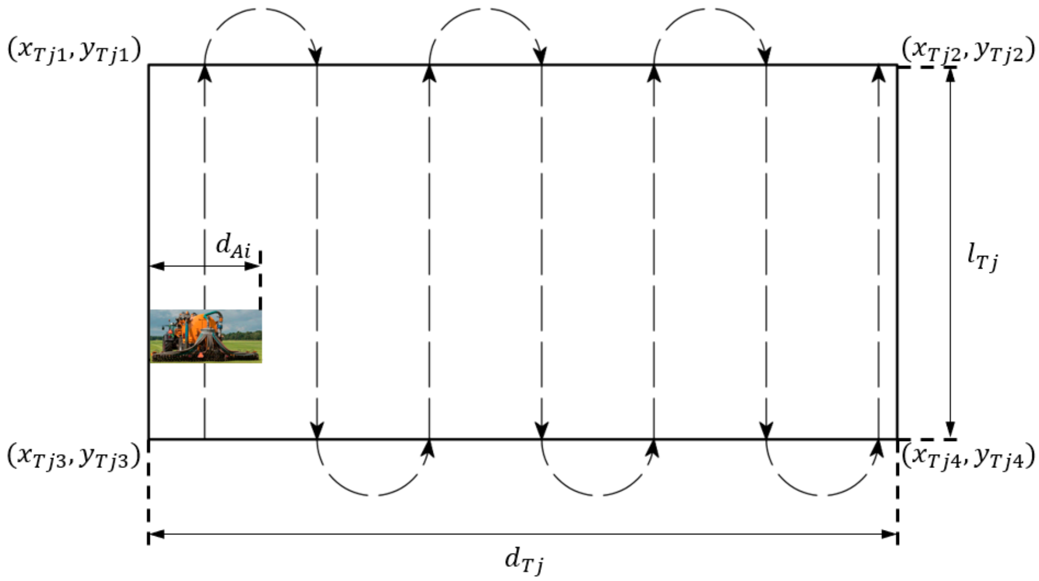

Figure 1. Operation mode diagram of a fertilizer applicator.

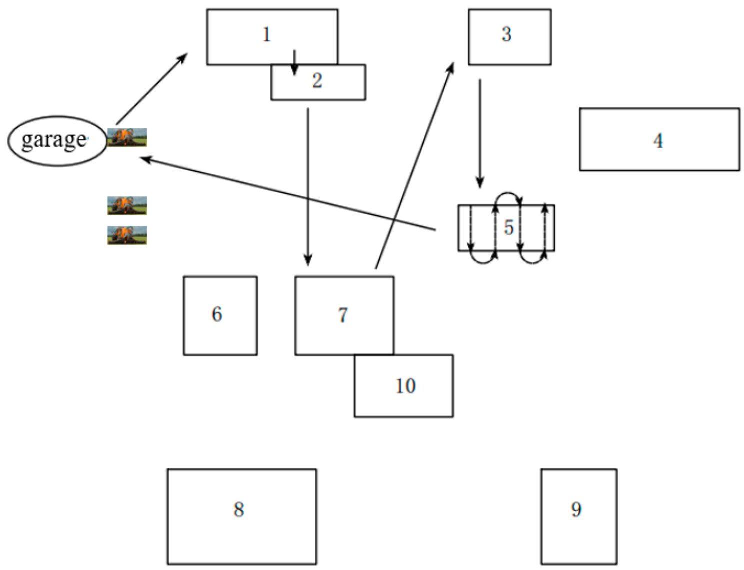

Figure 2. Schematic diagram of the fertilizer applicators operating in the order of distribution.

Considering the actual situation, different fields require different amounts of fertilizer due to different fertility conditions, and fields with a large amount of fertilizer have low operating speeds of fertilizer applicators. Moreover, when a fertilizer applicator's operating time is close to the maximum operating time, the fertilizer applicator will return to the garage and continue to operate the next day.

There are multiple fertilizer applicators for applying fertilizer to multiple fields, and the main goal is to minimize the final total completion time of all fertilizer applicators. Based on the existing information on fertilizer applicators and fields, the task allocation scheme of fertilizer applicators can be designed, including the fields of each fertilizer applicator, the order in which the fields are operated, and the number of days of operation.

For the convenience of research, this study makes the following assumptions for the considered problem:

- According to the amount of applied fertilizer, the fields are classified into several categories, including positive large, positive small, medium, negative small, and negative large, which correspond to different operating speeds of fertilizer applicators;

- All fields can be fertilized by any one fertilizer applicator, and the speed of the fertilizer applicator is inversely proportional to the amount of fertilizer applied to the field;
- Each field can only be fertilized by one fertilizer applicator;
- The daily working hours of a fertilizer applicator shall not exceed the specified time;
- All fertilizer applicators start from the garage every day and return to the garage after the operation is completed or after the specified number of working hours;
- The completion of the field work represents the end of the task.

2.1.2. Fertilizer Distribution of Fertilizer Truck

The fertilizer used by all fertilizer applicators is transported by a fertilizer truck to the specified entrance of each field and then applied by each fertilizer applicator in each field. As mentioned before, a fertilizer truck starts every working day from the garage, then puts the fertilizer at the field entrance that needs to be operated on that day, and finally returns to the garage.

In actual situations, the amount of fertilizer transported by a fertilizer truck is limited, and a single transport might not be able to meet the amount of fertilizer required for all fields that need to be operated on that day. Therefore, multiple transports are required until all the fertilizer has been transported to the designated locations. When a fertilizer truck is dispatched in the morning, it is necessary to transport the fertilizer required for the first working field of each fertilizer applicator and then transport the fertilizer required for the remaining working fields. In the afternoon, the procedure is the same; first, it is necessary to transport the fertilizer required for the first working field of each fertilizer applicator in the afternoon and then transport the fertilizer required for the remaining fields.

Only one fertilizer truck transports the fertilizer that needs to be applied on a certain day. Aiming at the goal of the shortest total distance of a fertilizer truck, the number of times the fertilizer truck transports fertilizer on a specific day, the amount of fertilizer transported each time, and the distance traveled by the fertilizer truck is obtained based on the information on the fields and the fertilizer truck.

2.2. Model Construction

2.2.1. Task Allocation Model for Multi-Machine Collaborative Operation of Fertilizer Applicators

For the task allocation problem of multi-machine collaborative operation of fertilizer applicators, where there are m fertilizer applicators and n fields, the objective model of the problem is established considering the number of operation days and daily working hours of fertilizer applicators, to minimize the total completion time. The objective function of the model is expressed as follows:

$$f = min\left(\sum_{i=1}^{m}\sum_{j=1}^{H_i} t_{w_{ij}} + mh_{max}H_d + t_{w_d}\right) \tag{1}$$

$$H_d = \max_{1<i<m}(H_i) - \min_{1<i<m}(H_i) \tag{2}$$

$$t_{w_d} = \max_{1<i<m}\sum_{j=1}^{H_i} t_{w_{ij}} - \min_{1<i<m}\sum_{j=1}^{H_i} t_{w_{ij}} \tag{3}$$

where f is the cost of multi-machine collaborative operation of fertilizer applicators; h_{max} is the maximum number of working hours of a fertilizer applicator per day; H_i is the number of operational days of fertilizer applicator A_i; $t_{w_{ij}}$ is the number of working hours of a fertilizer applicator A_i on a day j; H_d is the difference between the maximum and minimum operational days of different fertilizer applicators; t_{w_d} is the difference between the maximum and minimum total working hours of different fertilizer applicators.

In this study, the total working hours of all fertilizer applicators are used as a criterion for judging the cost. The penalty function $mh_{max}H_d$ is introduced to prevent a large difference in the number of operational days of different fertilizer applicators, where the penalty variable H_d represents the difference between the maximum and minimum operational days of different fertilizer applicators, and mh_{max} is the penalty coefficient that denotes the maximum possible total working hours of all the fertilizer applicators in a day. Further, a penalty variable t_{w_d}, which represents the difference between the maximum and minimum total working hours of different fertilizer applicators, is also introduced to ensure that the total working hours of different fertilizer applicators do not differ significantly and to avoid an increase in the idle rate of the fertilizer applicators.

According to the operation sequence $\{T_{1'}, T_{2'}, \ldots, T_{r'}\}$ of a fertilizer applicator A_i, the number of operational days and the number of daily working hours of fertilizer applicator A_i can be obtained. The time when fertilizer applicator A_i continuously completes operation sequence $\left\{T_{1'}, T_{2'}, \ldots, T_{p'}, s_1', s_2'\right\}$ is recorded as $t_{i,T_{p'},s_1',s_2'}$, where $T_{1'}, T_{2'}, \ldots$ represent the field with an operational sequence $1, 2, \ldots$; $T_{p'}$ represents the field where the continuous operation is terminated; s_1' and s_2' are the distances from the normal entrance of field $T_{1'}$ and field $T_{p'}$, representing the positions where the fertilizer applicator enters field $T_{1'}$ and leaves field $T_{p'}$, respectively. The last exit position of a fertilizer applicator needs to be on the same side as a specified entrance or exit position on every operational day.

(1) Daily operational fields and sequences

To determine the daily operational sequence of a fertilizer applicator A_i, the following symbols are defined:

$T_{p+1'}$ is the next operational field after field $T_{p'}$; $d_{Tp'}$ is the width of field $T_{p'}$; $d_{T(p+1)'}$ is the width of field $T_{p+1'}$; d_i is the operational width of a fertilizer applicator A_i; $t_{i,T_{p'},s_1',d_{Tp'}}$ is the time consumed by fertilizer applicator A_i to work continuously until it completely finishes field $T_{p'}$ and returns to the garage; $t_{i,T_{p+1'},s_1',d_{T(p+1)'}}$ is the time consumed by fertilizer applicator A_i to work continuously until it completely finishes field $T_{p+1'}$ and returns to the garage; $t_{i,T_{p+1'},s_1',kd_i}$ is the time consumed by fertilizer applicator A_i to work continuously until it completes k columns of field $T_{p+1'}$ and returns to the garage, where $k = 1, 2, \cdots, \left\lceil \frac{d_{T(p+1)'}}{d_i} \right\rceil$, and $\lceil \cdot \rceil$ is the upwards rounding symbol.

When the condition of $t_{i,T_{p'},s_1',d_{Tp'}} < h_{max} < t_{i,T_{p+1'},s_1',d_{T(p+1)'}}$ is satisfied, there are four possible cases:

- $t_{i,T_{p+1'},s_1',d_i} > h_{max}$;
- $t_{i,T_{p+1'},s_1',d_i} < h_{max} < t_{i,T_{p+1'},s_1',2d_i}$ and a fertilizer applicator A_i leaving field $T_{p+1'}$ is on the other side of the specified entrance or exit point;
- $t_{i,T_{p+1'},s_1',d_i} < h_{max} < t_{i,T_{p+1'},s_1',2d_i}$ and a fertilizer applicator A_i leaving field $T_{p+1'}$ is on the side of a specified entrance or exit point;
- $t_{i,T_{p+1'},s_1',kd_i} < h_{max} < t_{i,T_{p+1'},s_1',(k+1)d_i}, (k \geq 2)$.

In Cases 1 and 2, the operational sequence is $\left\{T_{1'}, T_{2'}, \ldots, T_{p'}, s_1', d_{Tp'}\right\}$, whereas in Cases 3 and 4, if a fertilizer applicator A_i that leaves a field $T_{p+1'}$ is on the side other than that of the specified entrance or exit point, then the operational sequence is $\left\{T_{1'}, T_{2'}, \ldots, T_{p+1'}, s_1', (k-1)d_i\right\}$; if a fertilizer applicator A_i that leaves a field $T_{p+1'}$ is on the side of the specified entrance or exit point, then the operational sequence is $\left\{T_{1'}, T_{2'}, \ldots, T_{p+1'}, s_1', kd_i\right\}$.

(2) The continuous operating time of fertilizer spreader A_i

The time $t_{i,T_{p'},s_1',s_2'}$ required for a fertilizer applicator A_i to complete an operational sequence $\left\{T_{1'}, T_{2'}, \ldots, T_{p'}, s_1', s_2'\right\}$ continuously consists of three parts:

- Travel time t_{i1} of fertilizer applicator A_i on the road;
- Time of field linear operation of fertilizer applicator A_i, which is labeled as time t_{i2};

- Field turnaround time t_{i3} of fertilizer applicator A_i.

$$t_{i,T_{p'},s_1',s_2'} = t_{i1} + t_{i2} + t_{i3} \tag{4}$$

$$t_{i1} = \frac{S_i}{v_i} \tag{5}$$

$$t_{i2} = \sum_{j=1}^{n} \frac{N_{ij} l_{Tj}}{v_{wj}} x_1(A_i, j) \tag{6}$$

$$t_{i3} = \sum_{j=1}^{n} (N_{ij} - 1) t_{ti} x_1(A_i, j) \tag{7}$$

where S_i is the total travel distance of a fertilizer applicator A_i on the road, as shown in Equation (8); N_{ij} is the number of columns of a fertilizer applicator A_i operating on a field T_j, as shown in Equation (9); v_{wj} is the speed of a fertilizer applicator operating on a field T_j, as shown in Equation (10); v_i is the speed of a fertilizer applicator A_i on the road; l_{Tj} is the length of a field T_j; t_{ti} is field turnaround time of a fertilizer applicator A_i; $x_1(A_i, j) = 1$ represents that the field T_j is the operational field of a fertilizer applicator A_i, and $x_1(A_i, j) = 0$ represents other situations.

The total travel distance S_i of a fertilizer applicator A_i on the road is calculated as follows:

$$\begin{aligned} S_i = &\sum_{j=1}^{n} s_1(A_i, T_j) x_2(A_i, j) + \sum_{j=1}^{n} s_2(A_i, T_j) x_3(A_i, j) \\ &+ \sum_{k=1}^{n} \sum_{l=1}^{n} s(A_i, T_k T_l) x_4(A_i, kl) \end{aligned} \tag{8}$$

where $s_1(A_i, T_j)$ is the distance of a fertilizer applicator A_i from the garage to the entrance of a field T_j; $s_2(A_i, T_j)$ is the distance of a fertilizer applicator A_i from the end position of a field T_j to the garage; $s(A_i, T_k T_l)$ is the distance of a fertilizer applicator A_i from a field T_k to the field T_l; $x_2(A_i, j) = 1$ represents that the field T_j is the first operational point of fertilizer applicator A_i, and $x_2(A_i, j) = 0$ represents other situations; $x_3(A_i, j) = 1$ represents that the field T_j is the last operational point of fertilizer applicator A_i, and $x_3(A_i, j) = 0$ represents other situations; $x_4(A_i, kl) = 1$ represents that the fields T_k and T_l are the operating points of fertilizer applicator A_i in the order of allocation, and $x_4(A_i, kl) = 0$ represents other situations.

The number of columns N_{ij} where a fertilizer applicator A_i operates on a field T_j is obtained as follows:

$$N_{ij} = \begin{cases} \left\lceil \frac{d_{Tj}}{d_i} \right\rceil, (j \neq 1', p') \\ \left\lceil \frac{d_{Tj} - s_1'}{d_i} \right\rceil, (j = 1') \\ \left\lceil \frac{s_2'}{d_i} \right\rceil, (j = p') \end{cases} \tag{9}$$

where $\lceil \cdot \rceil$ is the upwards rounding symbol; $1'$ is the serial number of the first operational field; p' is the serial number of the last operational field; d_{Tj} is the width of a field T_j; d_i is the working width of a fertilizer applicator A_i.

The speed v_{wj} of a fertilizer applicator operating on a field T_j is expressed as follows:

$$v_{wj} = \sum_{i=1}^{5} v_{wgi} g(T_j, i) \tag{10}$$

where v_{wgi} is the working speed of a fertilizer applicator A_i under the field classification into positive large, positive small, medium, negative small, and negative large fields; $g(T_j, i) = 1$ represents that the field T_j belongs to the ith classification among the five classifications, and $g(T_j, i) = 0$ represents other situations.

(3) Distance from garage to the field and between the fields

The distance between the garage and the n fields is represented by a square matrix D_d of order $(n+1)$ with a diagonal of zero, as shown in Equation (11), where the first row (column) represents the garage, and rows (columns) from the second row (column) to the last row (column) represent n fields.

$$D_d = \begin{bmatrix} d_{1,1} & \cdots & d_{1,n+1} \\ \vdots & \ddots & \vdots \\ d_{n+1,1} & \cdots & d_{n+1,n+1} \end{bmatrix} \tag{11}$$

$$d_{i+1,j+1} = \begin{cases} d_{garage,T_j}, (i = 0, j = \{1,2,\ldots,n\}) \\ d_{T_i,T_j}, (i,\ j = \{0,1,\ldots,n\} \text{ and } i \neq \text{j}) \end{cases} \tag{12}$$

where d_{garage,T_j} is the distance from garage to field T_j; d_{T_i,T_j} is the distance from field T_i to field T_j.

It is stipulated that the entrance and exit of a garage denote the intersection points, and the entrance and exit of a fertilizer applicator in the field are divided into two situations:

- The two vertices of the field are on the roadside, and the other two vertices are not on the roadside. As shown in Figure 3, for the two fields, it is stipulated that the left point of the two points on the roadside, like point p_1 or p_3, represents the entrance of a fertilizer applicator, and the point on the right, like point p_2 or p_4, denotes the exit of the fertilizer applicator;
- The four vertices of the field are all on the roadside. As shown in Figure 4, it is stipulated that the left point of the upper two points, like point p_1 or p_3, represents the entrance of a fertilizer applicator, and the point on the right, like point p_2 or p_4, is the exit of the fertilizer applicator.

The distance between the garage and n fields, from one place to the other, can be obtained by calculating the distance from its exit to the entrance of the other places using the Dijkstra algorithm.

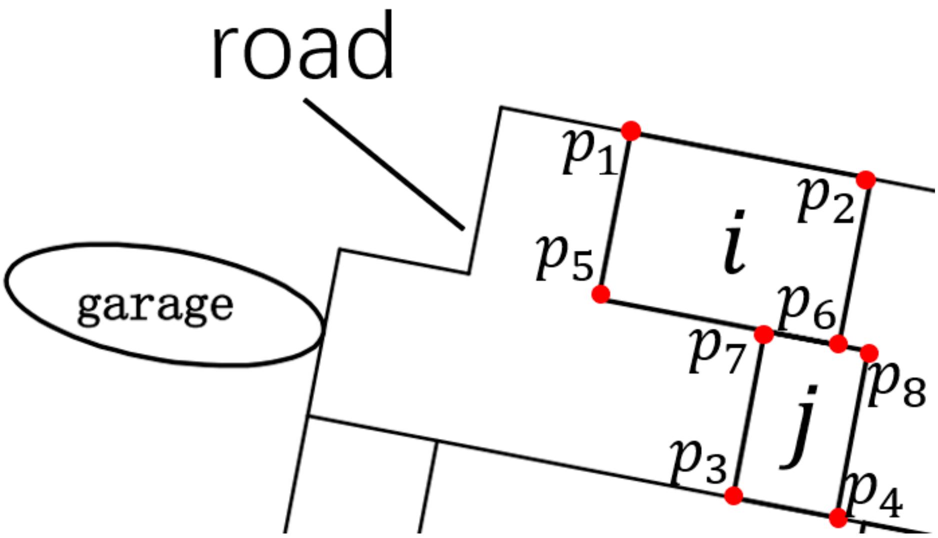

Figure 3. Schematic diagram of two vertices of a field on the roadside.

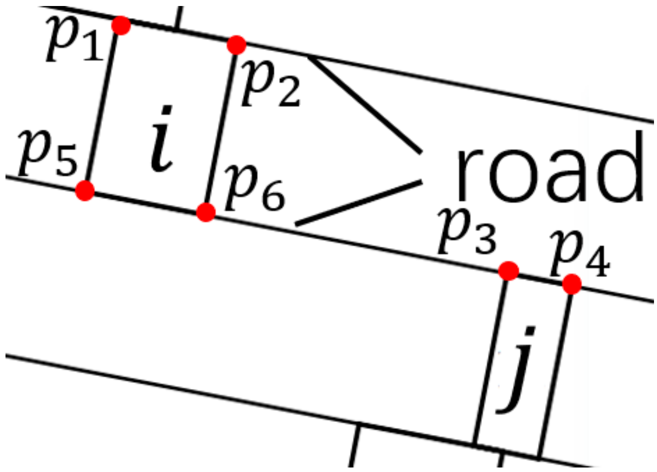

Figure 4. Schematic diagram of four vertices of a field on the roadside.

There are three special situations in the process of distance calculation:

- As shown in Figure 3, fields T_i and T_j are connected to each other on the opposite side of the entrance or exit side of the two fields. The distance from field T_i to field T_j is the distance from the point p_6 on the right side of the connected side of field T_i to the point p_7 on the left side of the connected side of field T_j; similarly, the distance from field T_j to field T_i is the distance from the point p_8 on the right side of the connected side of field T_j to the point p_5 on the left side of the connected side of field T_i;
- As shown in Figure 4, the opposite side of the entrance or exit side of field T_i is on the same road as the entrance or exit side of field T_j. The distance from field T_i to field T_j represents the distance from the point p_6 on the right side of the opposite side of the entrance or exit side of field T_i to the point p_3 on the left side of the entrance or exit side of field T_j;
- As shown in Figure 4, the opposite side of the entrance or exit side of field T_i is on the same road as the entrance or exit side of field T_j. The distance from field T_j to field T_i denotes the distance from the point p_4 on the right side of the entrance or exit side of field T_j to the point p_5 on the left side of the opposite side of the entrance or exit side of field T_i.

As given in Equation (13), a square matrix of order $n+1$ is used to represent the classification of situations from one location to another.

$$G = \begin{bmatrix} g_{1,1} & \cdots & g_{1,n+1} \\ \vdots & \ddots & \vdots \\ g_{n+1,1} & \cdots & g_{n+1,n+1} \end{bmatrix} \tag{13}$$

$$g_{ij} = \begin{cases} 0, (\text{Normal situation}) \\ 1, (\text{Situation1}) \\ 2, (\text{Situation 2}) \\ 3, (\text{Situation 3}) \end{cases} , i,j = \{1,2,\ldots,n+1\} \tag{14}$$

The distance of a fertilizer applicator A_i from a garage to the field T_j defined by Equation (8) is calculated as follows:

$$s_1(A_i, T_j) = d_{1,j+1} + s'_1 \tag{15}$$

when a fertilizer applicator completes a field and is positioned on the opposite side of the entrance or exit side, it is necessary to add the field length to the distance between the two points. For the convenience of calculations, this study uses x_{ij} to denote the side where a fertilizer applicator A_i enters field T_j and y_{ij} to denote the side where the fertilizer applicator A_i is located when it completes the operation task on field T_j; "1" represents the specified entrance or exit side, and "0" denotes the other side.

$$y_{ij} = \left(x_{ij} + N_{ij}\right)\%2 \tag{16}$$

where % is the modulus operator.

The distance of a fertilizer applicator A_i from a field T_j to the garage defined in Equation (8) is calculated as follows:

$$s_2\left(A_i, T_j\right) = d_{j+1,1} + \left|y_{ij} - 1\right| l_{Tj} - \left(d_{Tj} - s_2'\right) \tag{17}$$

Similarly, the distance of a fertilizer applicator A_i from a field T_k to the field T_l is calculated as follows:

For $g_{k+1,l+1} = 0$, the calculation formula is as follows:

$$\begin{gathered} s(A_i, T_k T_l) = d_{k+1,l+1} + |y_{ik} - 1| l_{Tk} \\ x_{il} = 1 \end{gathered} \tag{18}$$

For $g_{k+1,l+1} = 1$, the calculation formula is as follows:

$$\begin{gathered} s(A_i, T_k T_l) = d_{k+1,l+1} + y_{ik} l_{Tk} \\ x_{il} = 0 \end{gathered} \tag{19}$$

For $g_{k+1,l+1} = 2$, the calculation formula is as follows:

$$\begin{gathered} s(A_i, T_k T_l) = d_{k+1,l+1} + y_{ik} l_{Tk} \\ x_{il} = 1 \end{gathered} \tag{20}$$

Finally, for $g_{k+1,l+1} = 3$, the calculation formula is as follows:

$$\begin{gathered} s(A_i, T_k T_l) = d_{k+1,l+1} + |y_{ik} - 1| l_{Tk} \\ x_{il} = 0 \end{gathered} \tag{21}$$

2.2.2. Fertilizer Distribution Model of Fertilizer Truck

The operational field of a fertilizer truck defined for a specific day can be divided into four parts as follows. The first operational field of a fertilizer applicator in the morning is the first part; the remaining field of the fertilizer applicator in the morning is the second part; the first operation field of the fertilizer applicator in the afternoon is the third part; however, if the first operation field in the afternoon is finished in the morning, this part is regarded as the second part; the remaining field of the fertilizer applicator in the afternoon is the fourth part.

The transportation sequence of a fertilizer truck on a specific day is expressed by $\left\{T_1', T_2', \ldots, T_p'\right\}$, and the maximum amount of fertilizer transported by the fertilizer truck is denoted by F_{max}. Based on this, the number of transportations of the fertilizer truck and the distance of each transportation can be obtained. Assume that $F'_{T'_k}$ represents the amount of fertilizer that the fertilizer truck needs to transport to complete sequence $\left\{T_1', T_2', \ldots, T_k'\right\}$ at one time, and $F'_{T'_{k+1}}$ is the amount of fertilizer that the fertilizer truck needs to transport to complete sequence $\left\{T_1', T_2', \ldots, T_{k+1}'\right\}$ at one time. When $F'_{T'_k} < F_{max} < F'_{T'_{k+1}}$, a sequence $\left\{T_1', T_2', \ldots, T_k'\right\}$ is a transportation task, and so on, until all fields are completed.

As mentioned above, one fertilizer truck completes a transportation sequence. Taking the shortest total travel distance of a fertilizer truck as the optimization goal, the model of the considered problem is constructed, and the model objective function is defined as follows:

$$f = \sum_{i=1}^{N_t} d_{wi} \tag{22}$$

where d_{wi} is the travel distance of a fertilizer truck in the ith transportation process; N_t is number of transportations of a fertilizer truck; f is the cost for a fertilizer truck to complete the entire transportation sequence.

The amount of fertilizer required for each field is defined by Equation (23). Based on the amount of fertilizer for each field, which is necessary to complete all transportation tasks, the number of transportations of a fertilizer truck and the transportation sequence of each transportation can be obtained.

$$A_{fj} = l_{Tj}\left(d'_{Tj} - d''_{Tj}\right) \sum_{i=1}^{5} a_{fgi} g\left(T_j, i\right) \tag{23}$$

where A_{fj} is the amount of fertilizer applied to a field T_j; l_{Tj} is the length of a field T_j; d'_{Tj} is the distance from the position where a fertilizer applicator leaves a field T_j to the normal entrance of the field T_j; d''_{Tj} is the distance from the position where a fertilizer applicator enters a field T_j to the normal entrance of the field T_j; a_{fgi} is the unit amount of fertilizer of the fields under the field classifications into positive large, positive small, medium, negative small, and negative large fields; $g\left(T_j, i\right)$ is classification of a field T_j.

According to the operation sequence of a fertilizer truck and the entrance of each field, the distance traveled by the fertilizer truck to complete a certain transportation sequence d_t can be calculated as follows:

$$d_t = s\left(T_j\right) y_1\left(T_j\right) + s\left(T_j\right) y_2\left(T_j\right) + \sum_{k=1}^{n} \sum_{l=1}^{n} s(T_k T_l) y_3(T_k T_l) \tag{24}$$

where $s\left(T_j\right)$ is the distance between the garage and the entrance of a field T_j; $s(T_k T_l)$ is the distance between the entrances of fields T_k and T_l; $y_1\left(T_j\right) = 1$ represents that the field T_j is the first transportation point of a fertilizer truck, and $y_1\left(T_j\right) = 0$ represents other situations; $y_2\left(T_j\right) = 1$ represents that the field T_j is the last transportation point of a fertilizer truck, and $y_2\left(T_j\right) = 0$ represents other situations; $y_3(T_k T_l) = 1$ represents that the fields T_k and T_l are the transportation points of a fertilizer truck according to the distribution order, and $y_3(T_k T_l) = 0$ represents other situations.

The fertilizer stacking point on each field is specified as the entrance of a fertilizer applicator on that field under normal conditions; the shortest transportation distance of a fertilizer truck between the fertilizer stacking point on each field and the garage is represented by a symmetric square matrix D'_d of order $n+1$, with a diagonal of zero, which can be computed by the Dijkstra algorithm as follows:

$$D'_d = \begin{bmatrix} d'_{1,1} & \cdots & d'_{1,n+1} \\ \vdots & \ddots & \vdots \\ d'_{n+1,1} & \cdots & d'_{n+1,n+1} \end{bmatrix} \tag{25}$$

$$d'_{i+1,j+1} = \begin{cases} d'_{garage,T_j}, (i = 0, j = \{1, 2, \ldots, n\}) \\ d'_{T_i,T_j}, (i,\ j = \{1, 2, \ldots, n\}) \end{cases} \tag{26}$$

where d'_{garage,T_j} is the distance between the garage and field T_j; d'_{T_i,T_j} is the distance from field T_i to field T_j.

2.3. Improved Fireworks Algorithm

The traditional fireworks algorithm mainly includes three parts: explosion operator, mutation operator, and selection operator. The fireworks algorithm regards the location of each firework as a feasible solution to the problem. The explosion operator, where each firework has a different explosion radius with a different number of generated sparks, can be used to balance the global and local searches. The explosion operator defines that each firework, in a different explosion radius, generates a different number of new sparks. The better the fitness of the fireworks is, the smaller the explosion radius will be, and the more sparks will be generated by the explosion so as to conduct a local search. The worse the fitness of the fireworks is, the larger the explosion radius will be, and the fewer the sparks that will be generated by the explosion so as to conduct a global search [20]. As shown in Equations (27) and (28), the explosion radius and the number of generated sparks can be calculated. Further, the mutation operator selects fireworks randomly and performs Gaussian mutation on their random dimensions to increase population diversity. Finally, the selection operator mostly uses roulette for population selection.

$$R_i = R_{max} \frac{f(X_i) - \min\limits_{1<j<N} f\left(X_j\right) + \varepsilon}{\sum_{i=1}^{N}\left(f(X_i) - \min\limits_{1<j<N} f\left(X_j\right)\right) + \varepsilon} \tag{27}$$

$$Q_i = Q_{max} \frac{\max\limits_{1<j<N} f\left(X_j\right) - f(X_i) + \varepsilon}{\sum_{i=1}^{N}\left(\max\limits_{1<j<N} f\left(X_j\right) - f(X_i)\right) + \varepsilon} \tag{28}$$

where X_i is the ith firework; $f(X_i)$ is the fitness of the firework X_i; R_i is the explosion radius of the firework X_i; Q_i is the number of generated sparks; R_{max} is the maximum explosion radius of the firework X_i; Q_{max} is the maximum number of generated sparks; N is the number of populations; ε is a minimum value.

The new sparks generated in the explosion and mutation processes might be out of the specified boundary range in some dimensions, so they have to be cross-border processed. The cross-border process of a generated spark Y_i is defined as follows:

$$Y_i^k = \begin{cases} L_u - mod\left(Y_i^k - L_u, L_u - L_l\right), \left(Y_i^k > L_u\right) \\ L_l + mod\left(L_l - Y_i^k, L_u - L_l\right), \left(Y_i^k < L_l\right) \\ Y_i^k, \left(L_l < Y_i^k < L_u\right) \end{cases} \tag{29}$$

where Y_i^k is the kth dimension of a spark Y_i; L_u is the maximum boundary limit; L_l is the minimum boundary limit; $mod(\cdot)$ is subtraction operator.

The fireworks algorithm can search for more solutions in the solution space through the explosion operator and has better global search capabilities. It often achieves better solutions than other optimization algorithms in large-scale problems.

The traditional fireworks algorithm generates different numbers of sparks within different explosion radius according to the different fitness of the fireworks, which can better balance global search and local search [21]. However, it also has the problem, like other swarm intelligent algorithms, that it is easy to fall into a local optimal [22].

Aiming at the problem that the traditional fireworks algorithm can easily fall into a local optimal solution, this paper proposes the following improvement.

2.3.1. Coding and Discretized Decoding

The traditional fireworks algorithm is a continuous optimization algorithm, and its solution space is a continuous variable. The solutions to the task allocation problem of fertilizer applicators and the fertilizer distribution problem of fertilizer trucks are discrete values. Thus, it is necessary to use a discretized decoding method to decode and obtain possible solutions to the task allocation problem and fertilizer distribution problem.

(1) Multi-Machine Cooperative Operation Task Allocation of Fertilizer Applicators

Assume that m is the number of fertilizer applicators and n is the number of fields where fertilizer needs to be applied. By means of real number coding, each individual is an n-dimensional real number vector, and each element of the vector takes values from the range of $(0, m]$.

Further, n element positions of the individual vector represent n fields where fertilizer needs to be applied. An element from the range of $(0, 1]$ indicates that the field is operated by fertilizer applicator A_1, and an element from the range of $(k-1, k]$ indicates that the field is operated by a fertilizer applicator A_k. The element size represents the order of the operation of the corresponding field.

Table 1 shows an example of encoding and decoding with two fertilizer applicators and five fields. A five-dimensional real number vector is generated during coding, and the element size is in the range of $(0, 2]$. The element positions correspond to five fields, and the elements in intervals $(0, 1]$ and $(1, 2]$ represent the operations conducted by fertilizer applicators A_1 and A_2, respectively. The numerical size of an element represents the order of operation of an application fertilizer.

Table 1. Encoding and decoding examples.

Coding	0.35	1.32	1.27	0.65	1.51
Element position (corresponding to each field)	1	2	3	4	5
Fertilizer applicator	A_1	A_2	A_2	A_1	A_2
Order of operations	$A_{1,1}$	$A_{2,2}$	$A_{1,1}$	$A_{1,2}$	$A_{2,3}$

(2) Fertilizer Distribution of Fertilizer Truck

As mentioned above, one fertilizer truck delivers fertilizer to n fields, and fields in the model of the fertilizer distribution problem of a fertilizer truck are divided into four parts, having the number of fields of n_1, n_2, n_3, and n_4. The coding method proposed to solve the problem model is shown in Figure 5.

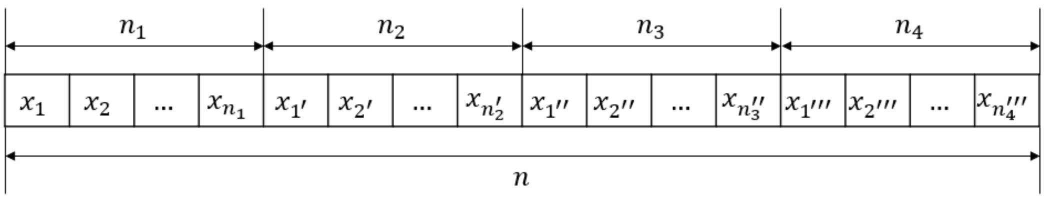

Figure 5. Coding method proposed to solve the fertilizer distribution problem.

In the coding process, the four regions correspond to the four types of fields, and each coding number has a value between 0 and 1. In the decoding process, the locations of the elements in each part correspond to the number of fields in each part arranged from small to large, and the order of the size of several numbers in each part represents the delivery order of fertilizer.

2.3.2. Chaos Initialization

In the traditional fireworks algorithm, fireworks are generated by random initialization. In this way, the location of fireworks will be unevenly distributed in the solution space, which can reduce the stability and accuracy of the algorithm. However, applying chaotic mapping to the population initialization can increase population diversity.

Chaotic mapping creates a sequence of chaotic variables generated by a simple deterministic system, which is used to replace the random number generator. The generated chaotic variables have the characteristics of nonlinearity, ergodicity, and randomness. In the intelligent optimization algorithm, chaotic mapping can often achieve better results than the random number generator.

Currently, there are many types of chaotic mapping methods. However, due to the strong ergodicity property, the logistic mapping method is selected in this study. The standard logistic mapping is defined as follows:

$$z_{k+1} = \mu z_k(1 - z_k) \tag{30}$$

where z_k is the kth chaotic variable, and $z_0 \notin \{0, 0.25, 0.5, 0.75, 1\}$; μ is parameter $\mu \in [0, 4]$, and its value in this study is set to four.

The sequence of chaotic variables obtained using Equation (30) can be used to initialize the population of the Chaos–Cauchy Fireworks Algorithm (CCFWA) using certain mapping rules. The mapping method of the chaotic variable sequence to the solution space is given by Equation (31).

$$X_i^k = b_l + z_{ik}(b_u - b_l) \tag{31}$$

where X_i^k is the kth dimension of fireworks X_i; b_l is the lower boundary of the solution space; b_u is the upper boundary of the solution space; z_{ik} is the kth chaotic variable of the chaotic variable sequence corresponding to fireworks X_i.

2.3.3. Cauchy Mutation

The traditional fireworks algorithm adopts the Gaussian mutation method, which has a short mutation step size and good local search ability. However, when an individual falls into a local optimum, it is difficult for the algorithm to exit the local optimum. Therefore, the Cauchy mutation method is considered in this study. Compared to the Gaussian mutation method, the Cauchy mutation method has a larger mutation step size, which can increase the population diversity, improve the global search ability of the algorithm, and prevent the algorithm from falling into the local optimum. The algorithm uses the Cauchy mutation spark instead of the Gaussian mutation spark. The Cauchy mutation spark Y_i generated by fireworks X_i is expressed as follows:

$$Y_i^k = X_i^k + Cauchy(0, 1) \tag{32}$$

where $Cauchy(0, 1)$ is the Cauchy distribution with the position and scale parameters of 0 and 1, respectively.

The generated Cauchy variant sparks also need to be cross-border processed using the cross-border process strategy.

2.3.4. CCFWA Process

In this paper, a fireworks algorithm based on discretized decoding, chaotic initialization, and Cauchy mutation is proposed, and its flowchart is shown in Figure 6.

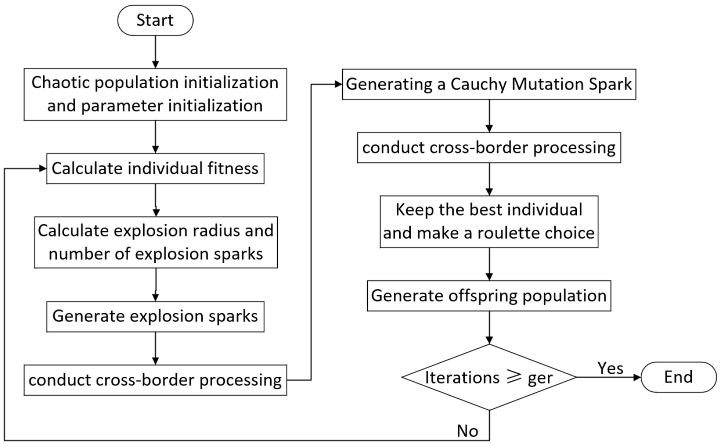

Figure 6. CCFWA flowchart.

3. Results and Discussion

3.1. Validation Experiment on Task Allocation Problem of Multi-Machine Cooperative Operation of Fertilizer Applicators

The Fireworks Algorithm (FWA), Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and the proposed CCFWA were used to solve the problem. Genetic Algorithm and Particle Swarm Optimization are two commonly used task allocation algorithms [23,24].

The experiment was conducted in a test area in Jimo District, Qingdao City, Shandong Province, where the number of fertilizer applicators was 3, the number of fields was 25, and the maximum working time of each fertilizer applicator was 8 h per day. The distribution of the fields is shown in Figure 7.

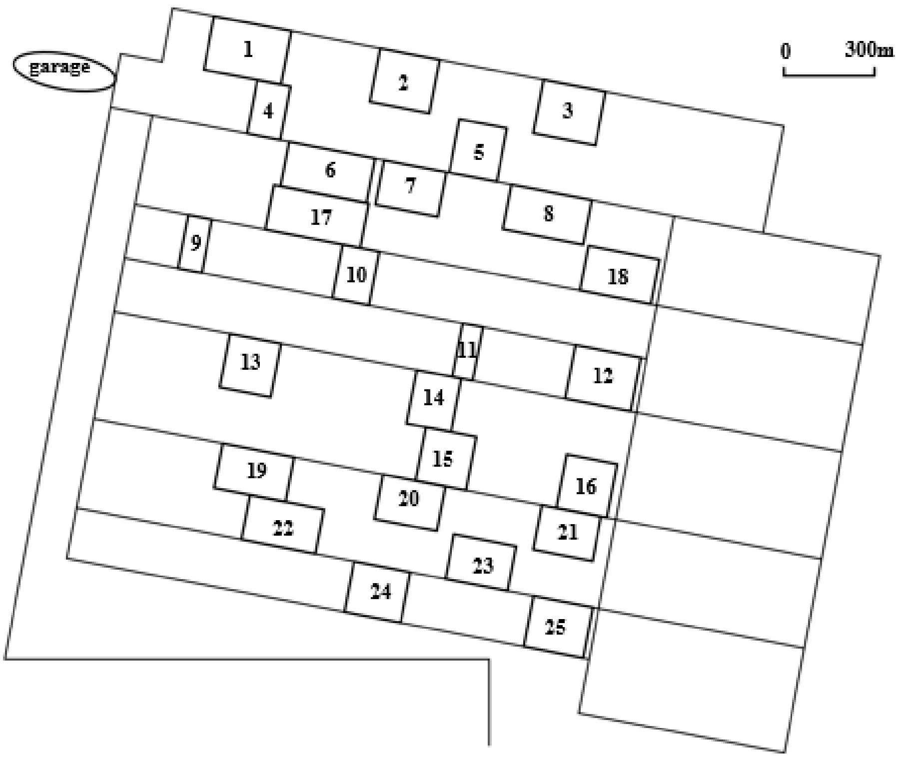

Figure 7. Schematic diagram of the experimental field.

The parameters of fertilizer applicators are shown in Table 2. The operational speed of each fertilizer applicator was in the range of 4–8 km/h. The operational speed of the fertilizer applicator on each field was determined by the fertility classification of the field.

Table 2. Parameters of fertilizer applicators.

Fertilizer Applicator Number	Working Width (m)	Working Speed (km/h)	Speed on the Road (km/h)	Turning Time (h)
1	2.4	4–8	10	0.005
2	2.1	4–8	10	0.004
3	1.8	4–8	10	0.003

The field parameters are shown in Table 3, where two important parameters, the length and width of each field, can be seen.

Table 3. Parameters of fields displayed in Figure 7.

Field Number	Width (m)	Length (m)	Area (m^2)
1	260	180	46,800
2	200	180	36,000
3	210	180	37,800
4	112	180	20,160
5	160	180	28,800
6	290	150	43,500
7	210	150	31,500
8	270	150	40,500
9	80	180	14,400
10	124	180	22,320
11	68	180	12,240
12	220	180	39,600
13	172	180	30,960
14	150	180	27,000
15	170	180	30,600
16	170	180	30,600
17	320	150	48,000
18	240	150	36,000
19	240	150	36,000
20	210	150	31,500
21	200	150	30,000
22	250	150	37,500
23	210	150	31,500
24	190	170	32,300
25	200	170	34,000

The information on field fertility, fertilizer application amount, and operation speed is presented in Table 4. The unit fertilizer application amount corresponding to the five field classifications of positive large, positive small, medium, negative small, and negative large fertility decreased sequentially, so the corresponding operational speed of the fertilizer applicator on the field increased sequentially and had the value of 4, 5, 6, 7, and 8 km/h, respectively.

Experiment 1: For the above-mentioned algorithms, using their simulation results, the graph of the number of iterations and the best fitness value were obtained, and their final fitness values and performances were compared. The parameter settings of the algorithms are shown in Table 5. The initial population size of all the four algorithms was set to 100, and the remaining parameters were selected from their common value range.

Table 4. Field classification parameters.

Field Classification	Field	Working Speed of Fertilizer Applicator (km/h)	Unit Fertilization Amount (kg/hm^2)
Positive large	1, 2, 3, 4	4	230
Positive small	5, 6, 7, 8, 9, 10, 11	5	215
Medium	12, 13, 14, 15, 16, 17, 18	6	200
Negative small	19, 20, 21, 22	7	185
Negative large	23, 24, 25	8	170

Table 5. Algorithm parameter settings.

Algorithm	Parameter Settings
FWA	Population size: 100; Maximum explosion radius: 1000; Maximum number of sparks: 2000; Number of variation sparks: 60
GA	Population size: 100; Crossover probability: 0.8; Mutation probability: 0.1
PSO	Population size: 100; Inertia weight: 0.8; Self-learning factor: 0.5; Group learning factor: 0.5
CCFWA	The same parameters as for the FWA

The comparison results of the fitness value of the four algorithms are shown in Figure 8, where it can be seen that the GA was prone to premature convergence and fell into a local optimum. Compared with the GA, the PSO could break through the local optimum in the early stage, but it could still fall into a local optimum in the middle and later stages. The FWA had a fast convergence speed in the early stage and could break through a local optimum, but there was still the possibility of falling into a local optimum in the middle and late stages. The proposed CCFWA could continuously break through the local optimum in the middle and late stages while ensuring the convergence speed, achieving better global search ability than the other algorithms. Among the four algorithms, the final fitness value of the CCFWA was the best.

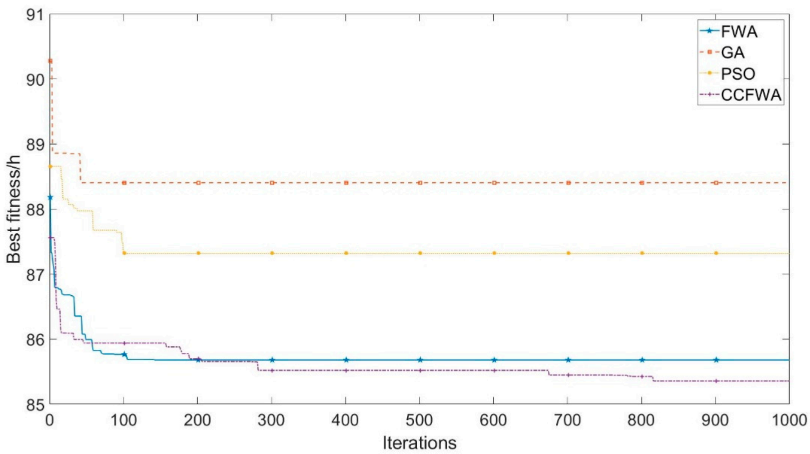

Figure 8. Comparison of fitness values of the four algorithms.

Experiment 2: This experiment was conducted to verify the ability of the proposed CCFWA to solve the task allocation problem of fertilizer applicators. The FWA, GA, PSO, and CCFWA algorithms were run 20 times each. Statistical analysis was carried out using four evaluation indicators: average value, variance, minimum value, and maximum value.

The statistical results of the minimum cost of the four algorithms are shown in Table 6, and from the perspective of the mean value, the four algorithms arranged in order of effectiveness were the CCFWA, FWA, PSO, and GA. The variance of the proposed CCFWA was much smaller than those of the other three algorithms, showing a reduction of 48%, 141%, and 139%, respectively. Considering comprehensively, the CCFWA could provide a better and more stable solution than the other three algorithms.

Table 6. Comparison of statistical results of the algorithms.

Statistic	FWA	GA	PSO	CCFWA
Mean value	85.522	87.789	86.919	85.004
Variance	0.173	0.280	0.282	0.117
Minimum value	84.741	86.580	85.544	84.440
Maximum value	86.455	88.745	88.087	85.793

Table 7 shows the optimal results obtained among the 20 results of the CCFWA, including the number of working days, daily working time, working route, and the position of the last field when the working process was finished (i.e., the distance between the ending position and the normal entrance of the field). For fertilizer applicator 1, in the results on the first day, 9→17→10 means that the operation route was from the garage through fields 9, 17, and 10 to the garage; 124 m means that the position of the fertilizer applicator leaving field 10 was 124 m from the entrance of field 10; 7.738 h means that the operating time of the fertilizer applicator was 7.738 h. The results obtained for the next few days were the same. On each day, the position of the fertilizer applicator entering the first field was determined by the departure position on the previous day, except that the position of the fertilizer applicator entering the first field on the first day was the entrance position of the field. If the departure position on the previous day was not the exit position of the field, the entry position was the departure position of the field, but if it was the exit position of the field, the entry position was the entrance position of the next field.

Table 7. Optimal results of the CCFWA.

Fertilizer Applicator Number	Daily Working Situation			
	1	2	3	4
1	9→17→10 124 m 7.738 h	15→14→13 172 m 7.697 h	2→3 168 m 7.998 h	3→12 220 m 4.714 h
2	19→16→7 105 m 7.991 h	7→6→4 54.6 m 7.960 h	4→1 260 m 7.589 h	20→11 68 m 4.425 h
3	5→8 230.4 m 7.996 h	8→21→25→22 79.2 m 7.996 h	22→24→23 210 m 7.984 h	18 240 m 4.170 h

3.2. Verification Experiment on Fertilizer Distribution Problem of Fertilizer Truck

In this experiment, the best result obtained by the CCFWA in Experiment 2 was used as input, and the fertilizer truck could transport up to 2 tons of fertilizer at a time; these data were used to determine the number of times per day the fertilizer trucks transported fertilizers along with the order of each transport.

The best results obtained by the CCFWA are shown in Tables 7 and 8. Table 8 shows the daily amount of fertilizer used in each field during the four-day fertilization operation.

Table 9 presents the fertilizer distribution scheme obtained by the CCFWA. Since there were not many fields that needed to be transported every day, an optimal allocation scheme could be obtained by the exhaustive method, and the optimal result obtained by the exhaustive method was consistent with the result obtained by the CCFWA. However, the exhaustive method is time-consuming and labor-intensive. When the number of fields to be transported increases every day, the time required for solving the fertilizer distribution scheme by the exhaustive method increases exponentially, making it difficult to obtain the solution. Therefore, using the proposed CCFWA to solve the fertilizer distribution problem considered in this study is more effective and convenient.

Table 8. The amount of fertilizer required by each field every day.

Field Number	**Daily Fertilization Amount (kg)**			
	Day 1	**Day 2**	**Day 3**	**Day 4**
1	0	0	1076	0
2	0	0	828	0
3	0	0	695.5	173.9
4	0	226	237.6	0
5	619.2	0	0	0
6	0	935.3	0	0
7	338.6	338.6	0	0
8	743	127.7	0	0
9	309.6	0	0	0
10	479.9	0	0	0
11	0	0	0	263.2
12	0	0	0	792
13	0	619.2	0	0
14	0	540	0	0
15	0	612	0	0
16	612	0	0	0
17	960	0	0	0
18	0	0	0	720
19	666	0	0	0
20	0	0	0	582.8
21	0	555	0	0
22	0	219.8	474	0
23	0	0	535.5	0
24	0	0	549.1	0
25	0	578	0	0

Table 9. The fertilizer truck distribution scheme solved by the CCFWA.

Statistic		**1**	**2**	**3**	**4**
Transport order	1	9→19→5	7→8→15→14	4→22→2	3→20→11→12
	2	8→16	6→4→13	24→1	——
	3	17→10→7	22→25→21	3→23	——
Transport distance (m)	1	5734	7370	7070	9490
	2	6020	3484	6070	——
	3	4024	6620	7760	——
Total transport distance (m)			15,778	17,474	20,900

4. Conclusions

This study considers the situation of different fertility of fields in practical operation scenarios, which leads to different operation speeds of fertilizer applicators in the field, and addresses the problem of multi-machine cooperative operation of fertilizer applicators and cooperative distribution of fertilizers from a fertilizer truck in fields with different fertility. To solve the considered problem, this study proposes the CCFWA, which improves some of the operations of the traditional fireworks algorithms. The verification experiments show that the CCFWA has better solution quality compared to the traditional FWA, PSO algorithm, and GA in task allocation of multi-machine cooperative operation of fertilizer applicators, and the variance is reduced by 48%, 141%, and 139%, respectively, with a higher stability of the solution. In addition, by using the proposed CCFWA, the problem of cooperative distribution of fertilizer from a fertilizer truck can be solved in a more effective and convenient way compared to the FWA, PSO algorithm, and GA. Finally, the proposed

CCFWA can realize multi-machine cooperative operation of fertilization task allocation of fertilizer applications and cooperative distribution of fertilizer from a fertilizer truck, according to multiple fertility fields.

However, this paper only studies the problem of multi-machine collaboration of fertilizer applicators and cooperative distribution of fertilizer from a fertilizer truck in the fertilization process. Multi-machine collaboration of agricultural machinery in other agricultural production processes has not been explored, such as multi-machine collaboration of harvesters and cooperative transportation of grain trucks in the harvesting process. For the problem of multi-machine collaboration for agricultural machinery in other processes, it is necessary to establish appropriate problem models and solution methods based on the characteristics of the problem in future research.

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