

Genetic algorithm solving the scheduling problem of large-scale power grid material quality inspection bases under multiple constraints

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Abstract. A mathematical programming model is constructed for the scheduling problem of large-scale power grid material quality inspection bases under complex and multi constraint conditions, with the completion time of material inspection, equipment utilization rate of the base, and total equipment load as multi-objective performance indicators. Based on the characteristics of the problem, a genetic algorithm is proposed as a tool for solving, and the encoding and decoding in the algorithm are specially designed for the detection base to ensure the generation of feasible solutions; Introducing roulette wheel to select populations, combining the characteristics of the problem to randomly mutate chromosomes, and using POX for chromosome crossover, in order to obtain the optimal solution to the problem. The proposed method effectively solves the scheduling problem of the testing base and greatly improves its operational efficiency by using the current quality testing example of dry-type transformers in the base for verification.

1 Introduction

The "Panoramic Quality Control" business chain is one of the three major business chains of State Grid Corporation of China's modern smart supply chain system. Material quality inspection is an important node of "Panoramic Quality Control" and the main means of implementing quality control business after the arrival of materials. At present, the quality inspection bases for power grid materials still mainly rely on manual arrangements, with low levels of scheduling intelligence, low detection efficiency, and inadequate equipment utilization [1]. Therefore, how to solve the scheduling problem of large-scale power grid material quality testing bases and improve the efficiency of material testing has become an urgent problem that needs to be solved in the power grid material supply chain.

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Currently, for solving flexible job shop scheduling problems similar to inspection bases, simulated annealing (SA), particle swarm optimization (PSO), taboo search (TS), and genetic algorithm (GA) are commonly used [2]. Ding Shuyang et al. [3] used particle swarm optimization algorithm to discretize PSO and make it suitable for solving scheduling problems, and then introduced operators to update subproblems and solve scheduling problems; Tang et al. [4] improved the local search ability of the algorithm by introducing simulated annealing algorithm to complete the local search for the optimal solution of the problem; Jia Zhaohong et al. [5] applied taboo search algorithm to solve complex multi-objective flexible workshop scheduling problems; Compared to other algorithms, genetic algorithms have the advantages of good robustness, strong universality, and excellent computational performance, as well as global search ability and implicit parallelism [6,7]. Many flexible job shop scheduling problems are solved using genetic algorithms, which can effectively solve complex scheduling problems, and the optimal solution obtained meets the requirements of the problem [8].

This article focuses on the scheduling problem of large-scale power grid material quality inspection bases. Taking the quality inspection of dry-type transformers in material inspection as an example, genetic algorithm is used to solve the problem. The encoding and decoding, population initialization and selection, gene crossover and mutation, and other links in the algorithm are designed to make it more in line with the actual situation of inspection base scheduling. The best scheduling solution is obtained by inputting dry-type transformer quality inspection data, effectively solving the inspection base scheduling problem.

2 Problem description

The scheduling problem of a large-scale power grid material quality testing base is described as follows: n power grid materials $\{E_1, E_2, \dots, E_n\}$ need to be tested on m testing equipment $\{M_1, M_2, \dots, M_m\}$. Each material contains multiple testing tasks arranged by the base, with a predetermined testing sequence. Each testing task can be performed on one or more devices, and the testing time varies depending on the testing equipment. In addition, the transportation of materials between each device will be carried out by AGVs, and the transportation time of AGVs will be determined by the distance between the testing devices. The scheduling objective is to determine suitable testing equipment for various testing tasks, determine the testing tasks and execution sequence of each material on each testing equipment, and determine the transportation tasks and sequence of each AGV. Due to the fact that each detection task can be detected on some optional detection equipment within the base, it is classified as part of the flexible job shop scheduling problem classification and contains AGV constraints [9].

The scheduling problem studied in this article takes the most common dry-type transformer in material inspection as an example. The quality inspection tasks for dry-type transformers are shown in Table 1. The inspection tasks required for each batch of transformers vary depending on the level of inspection. B-level inspection requires tasks J_1 to J_9 , while C-level inspection requires tasks J_4 to J_9 .

Table 2 shows the equipment and time required for level B and C detection tasks. For the setting of time units, the longest detection time (18h) required for task J_1 on M_1 is used as a reference to convert the time units for other tasks. In addition, for tasks that cannot be completed by the corresponding detection equipment, use -1 to exclude them. Due to the different functions and powers of various testing equipment within the base, the required time for the same testing task also varies. Therefore, it is necessary to find suitable testing equipment for the corresponding testing tasks of each material. In addition, it is necessary to

schedule transportation tasks for a limited number of AGVs, and the transportation time of AGVs is shown in Table 3.

Table 1. Quality inspection tasks for dry-type transformers.

Detection level		Detection task	Detection task
B-level		J_1	Temperature rise test
		J_2	Partial discharge test
		J_3	Lightning impulse test
	C-level	J_4	Winding resistance measurement test
		J_5	Voltage ratio measurement and connection group label verification test
		J_6	Measurement test of no-load loss and no-load current
		J_7	Short circuit impedance and load loss measurement test
		J_8	External voltage withstand test
		J_9	Induced voltage withstand test

Note: J_i represents the i -th detection task;

In the scheduling example used by the research institute, this batch of transformers includes four transformers, two of which undergo B-level testing and two of which undergo C-level testing. Eight testing equipment and three AGVs are required.

Table 2. Example of detection base scheduling problem.

Detection level		detection task	Testing equipment and required time							
			M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8
B-level		J_1	100	90	95	80	85	90	-1	-1
		J_2	-1	-1	-1	-1	-1	-1	1	-1
		J_3	-1	-1	-1	-1	-1	-1	-1	7
	C-level	J_4	3	4	3	4	3	4	-1	-1
		J_5	4	3	-1	-1	-1	5	-1	-1
		J_6	1	2	3	1	2	3	-1	-1
		J_7	1	2	1	2	1	2	-1	-1
		J_8	-1	-1	-1	-1	-1	2	-1	-1
		J_9	2	1	-1	-1	-1	2	-1	-1

Table 3. AGV transportation time at the testing base.

Detection equipment	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8
M_1	0	1	4	1	1	2	6	4
M_2	1	0	4	2	2	1	4	2
M_3	4	4	0	4	1	5	1	2
M_4	1	2	4	0	3	3	3	1
M_5	1	2	1	3	0	2	1	5
M_6	2	1	5	3	2	0	3	6
M_7	6	4	1	3	1	3	0	2
M_8	4	2	2	1	5	6	2	0

Note: M_m represents the m -th detection device;

When conducting detection tasks at the base, the following constraints must also be met:

- 1) The same testing equipment can only detect one item of material at the same time;

- 2) The same testing task for the same material can only be carried out by one testing equipment at the same time;
- 3) Once each testing task for each item of material begins, it cannot be interrupted. After the previous testing task for each item is completed, the next testing task can be arranged immediately, or it can be executed after other testing tasks for the same batch of materials are completed;
- 4) The priority of materials in the same batch is the same;
- 5) There is no sequential constraint between the testing tasks of different materials, but there is a sequential constraint between the testing tasks of the same material;
- 6) The same AGV can only transport one item of material at the same time;
- 7) All materials can be tested at zero time, all testing equipment is idle at zero time, and all AGVs are idle at zero time;
- 8) The transportation time of AGV is determined by the distance between different detection equipment;
- 9) AGV interference is not considered during transportation, and AGV can transport materials from the current testing equipment to the next testing equipment in the first time.

Based on the description of the detection base scheduling problem, this study considers three performance indicators simultaneously: the minimum maximum completion time for material detection, the maximum utilization rate of base detection equipment, and the minimum total load of base equipment; The objective functions for these three performance indicators are as follows:

Maximum Completion Time for Material Testing C_m

$$\min C_m = \min(\max(C_k)) \quad 1 \leq k \leq m \tag{1}$$

In equation (1), C_k is the completion time of equipment C_m ;

Maximum usage rate of base detection equipment W_k

$$\min W_k = \min(\max(W_k)) \quad 1 \leq k \leq m \tag{2}$$

In equation (2), W_k is the usage rate of device W_k ;

Total load of base equipment W_T

$$\min W_T = \min \left(\sum_{k=1}^m W_k \right) \quad 1 \leq k \leq m \tag{3}$$

Simultaneously considering multiple constraints in the base, the optimal solution to the scheduling problem is obtained while satisfying the optimal objectives ^[10].

3 Genetic algorithm design

3.1 Chromosome encoding and decoding

When designing the genetic algorithm for the scheduling problem of testing bases in this article, a special design is made in the encoding method, using a multiple encoding method, that is, triple encoding of the testing equipment, tested materials, and AGV in the testing base to ensure the generation of the optimal solution ^[11].

For example, taking the data in Table 1 as an example, any generated chromosome code is:

[3, 1, 2, 2, 0, 1, 3, 0, 2, 3, 0, 2, 1, 3, 0, 3, 0, 1, 1, 0, 0, 1, 3, 2, 0, 1, 0, 0, 1, 1, 1, 2],

[2, 3, 0, 5, 4, 6, 0, 6, 0, 1, 7, 4, 7, 1, 1, 5, 5, 0, 0, 1, 1, 0, 1, 0, 1, 5, 5, 1, 0, 5, 0],
 [2, 0, 2, 1, 1, 0, 1, 0, 0, 1, 1, 0, 0, 1, 1, 0, 1, 1, 2, 2, 2, 1, 0, 0, 1, 0, 0, 0, 0, 0, 1, 1]

Among them, the first layer of chromosome coding is material coding, and the order in which each material code appears is the order in which it needs to be tested. The number 3 in the first position represents the first testing task for material 4. The number 3 reappears at position 7, indicating the chromosome code for the second testing task of material 4. The second layer is the corresponding equipment code for the material testing task, and the third layer is the AGV code, indicating the AGV number of the current equipment going to the next equipment. For the scheduling problem of testing bases, unlike solving traditional flexible job shop scheduling problems, there are more hierarchical requirements for coding. In addition to basic material coding and testing equipment coding, it is also necessary to code the AGV that executes transportation tasks between equipment [12].

During the decoding process, the testing task arrangement for each item of material can be obtained based on the material coding section, and the execution time of the testing task can be obtained based on the testing equipment coding. The proposed chromosome encoding and decoding processes were designed at the AGV level, ensuring the rationalization of material detection task sequence and equipment allocation in the testing base. The AGV transportation was encoded and decoded to ensure that the genetic algorithm can perform subsequent operations.

3.2 Population initialization

To ensure the global search capability of the algorithm, the selected individuals should be evenly distributed in the given solution space as much as possible. In the study, the Hamming distance method was used to calculate the differences between individuals, in order to determine whether to generate the individual. Among them, Hamming distance D_{ij} calculate the number of digits where chromosomes i and j have different values at the same gene locus using the formula (4).

$$D_{ij} = \sum_{k=1}^L \eta_k \tag{4}$$

In the formula: L is the selected chromosome coding length,

$$\eta_k = \begin{cases} 0, & d_{ik} \neq d_{jk} \\ 1, & d_{ik} = d_{jk} \end{cases}$$

The steps for initializing a population using the Hamming distance method are as follows:

- 1) Perform random selection to obtain the first individual;
- 2) If the selected individual $i > 1$, measure the Hamming distance D_{ij} between this individual and the i -1st individual. If the obtained result is greater than p , individuals are randomly selected again until the calculated $D_{ij} \geq p$, where p is a positive number \leq chromosome length;
- 3) Repeat step 2) until the population initialization is complete.

3.3 Selection operation

The selection of high-quality individuals in algorithm design adopts a roulette wheel strategy. The probability of selection is related to the individual's adaptability. The stronger the adaptability, the greater the probability of being selected. This can not only improve the global convergence speed, but also ensure population diversity by having a certain

probability of selecting suboptimal individuals. The specific implementation steps are as follows:

- 1) Take equations (1), (2), and (3) as the objective functions Fitness (i) in the scheduling algorithm studied in this paper;
- 2) Calculate the corresponding fitness value (i) for each individual in the population;
- 3) Sum up the fitness values of all individuals in the population obtained in step 1);
- 4) Calculate the probability of individuals being selected within the population using formula (5):

$$q_j = \frac{\text{Fitness}(i)}{\sum_{i=1}^j \text{Fitness}(i)} \quad (5)$$

Select a random number K within the interval [0,1] and arrange it in descending order to obtain $K=\{k_1, k_2, \dots, k_n\}$, and initialize $i=1, j=1$;

6) Comparing k_i and q_j , if k_i is less than q_j , individual j can be selected, where $i=i+1$, otherwise $j=j+1$;

7) Repeat step 6 until $i>N$, where N is the number of individuals in the population.

3.4 Cross operation

In genetic algorithm design, crossover operation is of great significance, as it enables the population to inherit excellent genetic features from its parents through iteration. Based on the problem characteristics of detection base scheduling, algorithm design is carried out in cross operations, and POX cross operations are proposed for the tested materials, greatly reducing unnecessary solving time and improving algorithm solving efficiency [14]. POX crossover greatly preserves the excellent detection order in the parent scheduling scheme, which introduces the crossover rate parameter P_c with a range interval of [0,1]. The specific implementation steps are as follows:

1) Create a random number $\text{rand} \in [0,1]$, if $P_c > \text{rand}$, proceed to the next step, otherwise exit the operation;

2) Randomly select two chromosomes from the population as crossing parents;

3) Divide the set of tested materials from the parent into N_1 and N_2 groups, with a minimum of 2 materials in each group;

4) Retain the gene locus containing group N_1 material in parent ①, and set the gene locus containing group N_2 material in parent ① to 0. Then, insert the gene containing group N_2 material in parent ② into position 0 in parent ① in the original order;

5) Retain the gene locus containing group N_1 material in parent ②, and set the gene locus containing group N_2 material in parent ② to 0. Then, insert the gene containing group N_2 material in parent ① into the 0 position in parent ② in the original order;

As shown in Figure 1, the crossover step is to randomly select two parent chromosomes from the population, where the material gene encoding of parent ① is [1, 3, 3, 2, 4, 1, 4, 2, 3, 1, 1, 2, 2, 2, 4, 1, 2, 1, 4, 3, 2, 1, 3, 1, 3, 1, 4, 2, 4, 1], and the material gene encoding of parent ② is [2, 2, 4, 4, 4, 1, 1, 3, 2, 4, 4, 3, 1, 1, 4, 2, 2, 3, 1, 1, 1, 1, 1, 1, 3, 2, 1, 2, 2], grouped by the material collection $\{1, 2, 3, 4\}$, $N_1=\{1, 4\}$, $N_2=\{2, 3\}$. Continue with steps 4) and 5) to complete the POX crossover operation and obtain offspring with excellent characteristics of the parent.

3.5 Mutation operation

To improve the local search ability of the algorithm, the mutation operation in the algorithm

mutates the detected material genes, detection equipment genes, and AGV genes in the chromosome. Among them, the detection equipment genes and AGV genes undergo random mutation, while the detected material genes will be achieved by randomly exchanging the positions of the two genes due to the existence of different material detection tasks. Due to the change in the gene of the tested material, the corresponding selection set of testing equipment has also been changed. The order of the selected testing equipment corresponding to the two selected material genes will be saved, so that the order can still be used after exchanging positions [15].

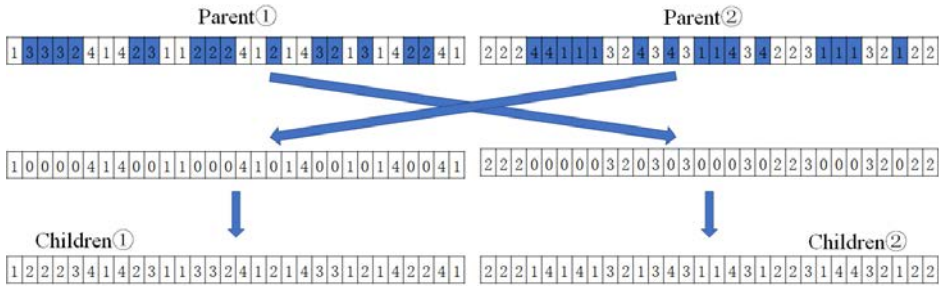


Fig. 1. POX crossover.

4 Algorithm application results

Implement the improved genetic algorithm proposed in this article, which is programmed in Python and executed on PyCharm Community Edition 2021.3.2. The Python version is 3.9, and the program runs in an 8GB memory environment with a Core i5 processor and a 64 bit Windows 10 operating system on a personal computer. The key parameters in the algorithm are set as follows: population size $P_s=200$, crossover rate $P_c=0.8$, mutation rate $P_m=0.2$, and iteration number $G=100$; The algorithm validation for the quality inspection task of this batch of dry-type transformers given in Table 1.2 will result in the shortest scheduling time of 129.0, and the optimal chromosome is:

- [3, 2, 0, 3, 0, 3, 1, 0, 3, 0, 0, 2, 1, 2, 1, 2, 3, 1, 0, 1, 1, 0, 0, 2, 1, 1, 1, 3, 0, 2],
- [1, 3, 4, 0, 6, 2, 1, 7, 4, 2, 0, 5, 6, 1, 7, 1, 5, 0, 0, 1, 1, 3, 5, 5, 0, 5, 1, 5, 5, 1, 5, 1, 0],
- [2, 0, 0, 2, 0, 1, 1, 1, 1, 0, 0, 2, 1, 2, 1, 0, 1, 1, 2, 2, 1, 2, 1, 2, 1, 0, 0, 1, 1, 2, 0]

Visualize the scheduling results and obtain the optimal scheduling plan Gantt chart, as shown in Figure 2. The horizontal axis represents the detection time, and the vertical axis represents the detection equipment used. A0, A1, and A2 in the chart represent the transportation of AGV materials between devices, and $O_{i,j}$ represent the execution of quality inspection tasks for each transformer. For example, if $O_{0,1}$ appears on device 5, 1 represents the arrangement of the first inspection task for transformer 1. As it is the first task for the transformer, AGV transportation is not required. $O_{0,2}$ on device 7 represents the arrangement of its second inspection task. A0 shown earlier indicates that after completing the first task on device 5, transformer 1 is arranged by AGV 1. Transport to device 7, similarly, other items represent the same, and the blank space in the figure indicates that the detection device is idle.

$O_{i,j}$ represents the execution of quality inspection tasks for each transformer, and A_n represents the transportation execution of each AGV;

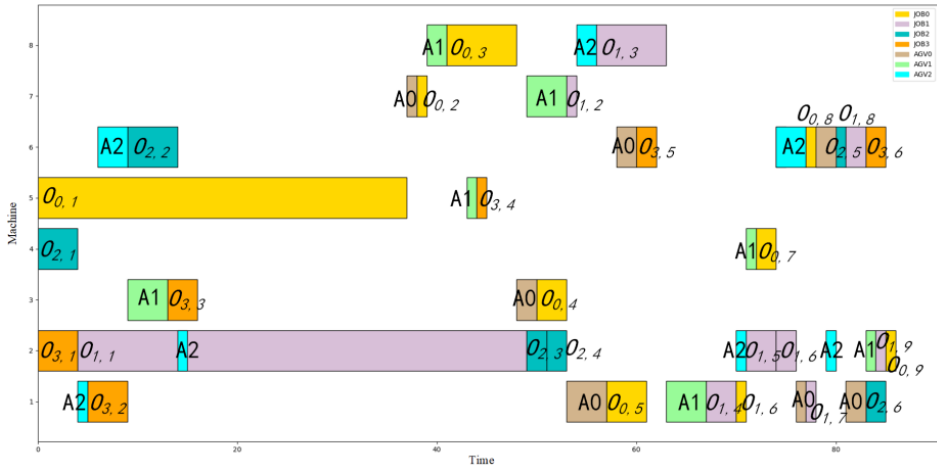


Fig. 2. Gantt chart for quality inspection scheduling of dry-type transformers.

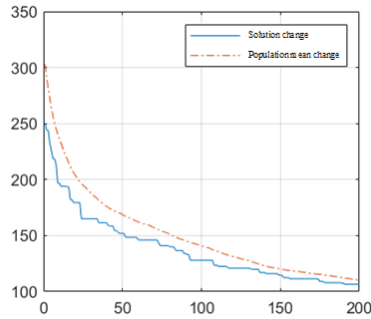


Fig. 3. Changes in population solutions and mean changes.

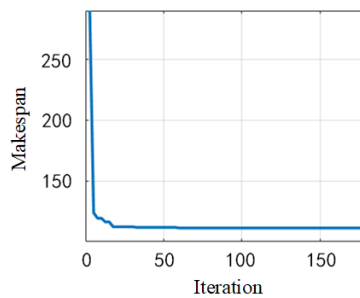
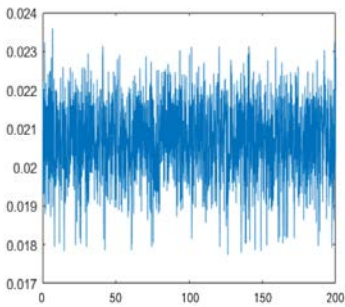


Fig. 4. Changes in minimum population fitness. **Fig. 5.** Changes in global optimal solution.

In addition, the changes in the population solution and mean are shown in Figure 3, the changes in the minimum population fitness are shown in Figure 4, and the changes in the global optimal solution are shown in Figure 5. The above verification results show that the proposed method of using genetic algorithm to solve the scheduling problem of large-scale power grid material quality inspection bases can effectively obtain the optimal solution, and the scheduling calculation process is fast and efficient, with a high degree of convergence of the optimal solution.

5 Conclusion and outlook

This article focuses on the scheduling problem of large-scale power grid material quality inspection bases under multiple constraints, using genetic algorithm to solve the problem and considering multiple performance objectives. The algorithm validation was carried out using the quality inspection task of dry-type transformers in actual operation of the testing base. The optimal scheduling solution obtained can solve the scheduling problem of the testing base, greatly improving the efficiency compared to the existing scheduling situation. This validates the feasibility and effectiveness of the genetic algorithm proposed in this paper for solving the demodulation problem of the testing base.

In addition, in subsequent research on this scheduling problem, improved algorithms and algorithm fusion can be applied for targeted design to meet more complex base scheduling needs, further improve the operational efficiency of detection bases, and accelerate the supply speed of power grid materials.

Declaration of Competing interest

We confirm that our work have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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