Multi-objective flexible job shop scheduling problem with triple bottom line theory-based sustainable objectives

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Abstract. The triple bottom line theory (TBL) is widely used in the field of sustainable development research. Based on the triple bottom line theory, this paper investigates a multi-objective flexible job shop scheduling problem with the consideration of sustainable objectives. A multi-population evolutionary algorithm with single-objective guide (MPEA/SG) is modified to solve this problem effectively by extending the MPEA/SG to discrete optimization problems. Our experiments show that considering TBL-based objectives in job shop scheduling is more conducive to the sustainability of the production process, and can effectively reduce the carbon footprint, E/T penalty cost and income difference.

1. Introduction
In fact, most medium and small-sized manufacturing enterprises are facing the problem of how to achieve sustainable development, they have an inescapable responsibility for the emission of greenhouse gas [1]. According to the Triple Bottom Line theory (TBL), if a company wants to achieve long-term development, it should take responsibilities from the economic, environmental and social [2]. Scheduling is an important factor affecting the development of manufacturing industry. A good scheduling can bring a lot of benefits to the enterprises, such as the improvement of production efficiency, cost savings, reduction of emissions, improvement of worker job satisfaction and so on.

At present, the FJSP (Flexible job shop scheduling problem) has gained more and more attention from domestic and abroad scholars [3-7]. However, the majority of previous researches lacked the consideration of goals in sustainable development. They usually focused on the classic goals, such as the total completion time, machine utilization, and production costs [8-12]. Aiming at helping manufacturing to better developing sustainability, this study combines the FJSP with TBL, which can achieve the purpose of energy conservation and emission reduction, while considering the social and economic goals. In the same time, we choose the MPEA/SG (A multi-population evolutionary algorithm with single-objective guide) based algorithm to solve this problem. At the end of this research, the feasibility and effectiveness of the production scheduling guided by TBL has been verified by the case study.

2. Problem statement
2.1. Problem description
The main function of a manufacturing system is to process raw materials into products. Generally speaking, the production system does not generate a direct carbon footprint during processing. As a
major part of the production system, the machine may be in the following states: start-up, warm-up, idling, processing and shutdown. The typical energy consumption of a machine is shown in Figure 1.

![Figure 1. Typical energy consumption of a machine.](image)

We can ignore the energy consumption of the start-up, shutdown and warm-up process when establishing the model, because the machine is turned on and off only once a day, and only the processing time and the idling time need to be considered separately. In order to build an emission model for the production system, we need to collect the data from electrical energy consumption and carbon emission factors, the expression is shown in the following:

\[
CF = E \cdot T \cdot \alpha
\]  

(1)

CF is the carbon footprint, E is the power consumption of the machine processing time, and \( \alpha \) is the carbon emission factor. The flexible job shop scheduling problem can be described as follows:

Parts \( \{P_1, \ldots, P_n\} \) must be processed on corresponding machines \( \{M_1, \ldots, M_k, \ldots, M_m\} \), which are operated by a group of workers \( \{W_1, \ldots, W_l, \ldots, W_w\} \), each part has a fixed delivery time, and the processing of each part involves a series of operations \( \{O_{i,1}, \ldots, O_{i,j}, \ldots, O_{i,m}\} \). There is a certain processing sequence between different operations of the same part, and the same operations can be operated by different workers on different machines. Different workers process the same operation on the same machine, due to the different settings of processing parameters, the power consumption also varies. In this scheduling system, workers almost have the same efficiency in operating the different machines. Based on the triple bottom line theory, this research optimizes three-objectives for the flexible job shop scheduling problem.

2.2. Triple bottom line theory-based scheduling objectives

According to the TBL theory, the enterprises need to take the responsibility from environmental, economic and social, therefore, three goals in this scheduling problem are considered as follows:

2.2.1. Environmental goal: Minimize the carbon footprint of production systems. On the premise of ignoring the energy consumption in the start-up, warm-up and shutdown processes, only the carbon footprint of the machining process and the idling process of the machine need to be considered separately.

\[
f_1 = \min TCP = \min(TCFP + TCFI)
\]  

(2)

In Equation (2), TCF represents the total carbon footprint of the production system, TCFP represents the carbon footprint generated by the machining process, and TCFI represents the carbon footprint generated by the machine during idling.
2.2.2. Economic objective: Minimize the cost for E/T penalty cost. With the promotion of the Just in Time (JIT) production model, how to reduce the inventory of the enterprise without delay is difficult for the enterprise. Therefore, this article chooses to minimize the cost of E/T penalty as the economic goal:

\[ f_2 = \min PC = \min(EC + TC) \] (3)

In Equation (3), PC means the total penalty cost, EC means the storage cost and TC means the tardiness penalty cost.

2.2.3. Social objective: Minimize income differences. There are two types of workers, the first one can operate the machines almost with the same efficiency, the another one is considered to have different skills which can operate machines with different efficiency [13]. This research has considered the first type of workers. In order to minimize the income differences caused by scheduling, we set the goal as follows:

\[ f_3 = \min DW = \min\left(\frac{\sum (SW - AW)^2}{L}\right) \] (4)

In Equation (4), SW is the personal salary, AW is the average salary of workers, DW means the income difference between workers, the total number of workers is L.

3. MPEA/SG-based multi-objective scheduling algorithm

3.1. Algorithm framework

The multi-population evolutionary algorithm with single-objective guide (MPEA/SG) was proposed in 2019 [14]. MPEA / SG uses the advantages of multi-group and single-objective optimization to balance the diversity and convergence of the evolutionary process. When compared with the other 9 advanced multi-objective algorithms (MOEA/D, NSGA-II and PESA-II etc.) have shown better performance.

However, the original MPEA/SG didn’t investigate the capability of solving discrete problems. In this paper, we address the problem of scheduling in manufacturing which belongs to the integer programming problem, so we extend the MPEA/SG to discrete optimization problems and modify this algorithm.

| Framework of MPEA / SG |
|------------------------|
| **Require:** N (population size), K (the number of subpopulations), \( N_k \) (the size of the \( K^{th} \) subpopulation), M (the number of objectives) |
| **Ensure:** final population is P |
| 1: randomly generate an initial population P with N individuals; |
| /* Stage 1: Parallel multiple population single objective optimization */ |
| 2: Randomly divide the population P into M sub-populations of the same size, \( P_1, \ldots, P_M \); |
| 3: Single-objective parallel optimization for each sub-population \( P_m \); |
| 4: M sub-populations \( P_m \) are merged into population P; |
| /* Stage 2: Parallel multi-population many-objective optimization */ |
| 5: Randomly divide the population P into K sub-populations with a population size of \( N_k \), \( P_1, \ldots, P_K \); |
| 6: Information Sharing between \( P_1, \ldots, P_K \), Guarantee the diversity of individuals in the population; |
| 7: Parallel multi-objective optimization for each subpopulation \( P_s \); |
| 8: Combine K sub-populations \( P_s \) into population P; |
| /* Stage 3: Single population multi-objective optimization */ |
| 9: Multi-objective optimization of population P; |
| 10: Get the final solution set P |
The appropriate optimization algorithm is selected for different stages, of which the genetic algorithm (GA) is selected in the first stage, and the NSGA-II is selected in the second and third stages.

3.2. Coding
In flexible job shop scheduling, the operations should be sequenced, meanwhile, the machines and workers needed to be allocated to the operation. In real life, machines are often operated by a fixed group of workers. Therefore, this research designs a two-layer coding chromosome which includes operations, machines and workers. The length of the chromosome is equaling to the number of total operations of one part. The whole chromosome is consisted of processing part and resource part. For example, there are two machines in the job shop. The M1 and M2 can both be operated by worker W1 and W2. The relationship can be expressed as a group: [G1 M1W1] [G2 M1W2] [G3 M2W1] [G4 M2W2], where [G1 M1W1] means the first group G1 contains worker W1 and machine M1.

| Part number | Operation number | G1 M1 W1 | G2 M1 W1 | G3 M2 W1 | G4 M2 W2 |
|-------------|------------------|----------|----------|----------|----------|
| P1          | O11              | 0        | 0        | 2        | 4        |
|             | O12              | 0        | 4        | 3        | 3        |
| P2          | O21              | 5        | 6        | 0        | 0        |
|             | O22              | 0        | 4        | 3        | 2        |

Table 1. Machining time.

Table 2. Chromosome coding expression examples.

As shown in Table 1, this problem is a dual-resource constrained flexible shop scheduling problem composed of two parts, two machines, and two workers. A machining time of "0" indicates that this group cannot process this operation. As shown in Table 2, the chromosome can be divided into OS and GS. The OS determines the processing sequence of part. From left to right, the number that appears k-th times in the OS means the k-th process of the part represented by the number, and GS represents the group number of the machine and the worker. The dimension of each individual can be explained as, for example, (O12; G1) is the fourth dimension of the chromosome, which means that the second operation of part P1 is processed by worker W1 on machine M2, that is, processed by third group G3, and the processing time is 3.

4. Numerical experiments
To verify the proposed model and algorithm, a flexible job shop from a real manufacturing enterprise machining valve guide is taken as an example. There are two lathes (M1, M2), two drilling machines (M3, M4) and two milling machines (M5, M6) in the job shop. The M1, M3 and M5 can be operated by worker W1 and W2, the remaining machines can be operated by W3 and W4. We have collected the idling power consumption data from the mechanical processing handbook: [M1-0.30 kW·h, M2-0.27 kW·h, M3-0.25 kW·h, M4-0.28 kW·h, M5-0.42 kW·h, M6-0.44 kW·h]. We will show the detail processing time and power consumption for P1 in Table 3:

Table 3. Processing time and power consumption for P1.
The tardiness penalty cost is 1.2 per unit time, the storage penalty cost is 0.8 (including storage costs), and the worker's salary is 30 yuan / hour. The carbon emission factor caused by power consumption can refer to the regulations of the State Administration of Standardization of the People’s Republic of China, which is 0.997 kg / kWh. Parameter settings: population size \( N = 90 \), the number of iterations in the different stage \( I_1 = 300, I_2 = 50, I_3 = 50 \), frequency of information sharing \( T = 4 \), crossover rate \( C = 0.8 \), mutation rate \( A = 0.2 \), number of objectives \( M = 3 \), subpopulation size \( N_k = 30 \), we can get the pareto solutions in Table 4:

| Solution's number | TCF | E/T penalty | Income difference |
|-------------------|-----|-------------|-------------------|
| 1                 | 19.71 | 1.00       | 20.23            |
| 2                 | 19.18 | 1.20       | 13.83            |
| 3                 | 18.97 | 1.80       | 6.06             |
| 4                 | 18.94 | 2.20       | 50.83            |
| 5                 | 18.88 | 2.6        | 36.23            |
| …                 | …    | …          | …                |
| 11                | 17.78 | 10.2       | 72.73            |
| 12                | 17.21 | 12.80      | 25.90            |

The Gantt chart for solution 12 which has the minimum carbon footprint is shown in Figure 2. The "101" in the picture means the first operation of part 1.

![Gantt chart for solution 12](image)

Figure 2. Gantt chart for solution 12.

In order to verify the superiority of multi-objective job shop scheduling combined with TBL, these solutions from the three-objective will be compared with corresponding single-objective and two-objective problems respectively.

4.1. Comparison with single-objective cases

This study selects genetic algorithms to solve single-objective FJSP. The solutions are as follows:

| Single-object optimal         | TCF | E/T penalty | Income difference |
|-------------------------------|-----|-------------|-------------------|
| Economic optimal              | 19.99 | 0.60       | 54.92             |
| Environmental optimal         | 17.21 | 13.20      | 98.90             |
| Society optimal               | 22.79 | 31.60      | 0.06              |

Economic optimality is the preferred goal for the enterprise when the TBL is not considered. From the Table 5, it can be found that when the economic cost is the lowest, neither the income difference
nor the carbon footprint is a reasonable solution. In particular, the worker's income difference is increased by 2.7 times when compared with the economic best solution in three-objective FJSP \((cost = 1.0 \quad TCFP = 19.71 \quad DW = 20.23)\). This is not a reasonable solution, on the one hand is not conducive to creating a fair and reasonable working environment for workers, on the other hand it is not conducive to guiding enterprises to implement low-carbon sustainable development. Similarly, solutions from environmental single-objective problems or social single-objective problems show the same trend.

4.2. Comparison with two-objective cases

Next, a comparison with dual-objective is conducted, which are divided into three groups:

- Group 1: economic goals & social goals
- Group 2: environmental goals & social goals
- Group 3: environmental goals & economic goals

We can get three groups of Pareto solution set, the solutions from Group 1 are showed in the following table:

| Solution’s number | TCF    | E/T penalty | Income difference |
|-------------------|--------|-------------|-------------------|
| 1                 | 22.82  | 31.60       | 0.06              |
| 2                 | 22.77  | 22.00       | 0.17              |
| 3                 | 21.34  | 19.00       | 0.23              |
| 4                 | 22.87  | 17.00       | 0.40              |
| 5                 | 20.39  | 15.00       | 0.56              |
| …                 | …      | …           | …                 |
| 11                | 20.66  | 1.60        | 5.42              |
| 12                | 21.02  | 1.00        | 5.83              |

From Table 6, it can be found that the solution of environmental goal is too high compared with the TBL based solutions in Table 4. The minimum carbon footprint in Table 6 is 19.80, which is higher than the maximum data in Table 4 (TCF=19.71). The same situation still exists in Group 2 and Group 3 when we only consider two objectives.

By comparing the two-objective with the three-objective, we can further affirm the necessity of considering the TBL in the production process, which can help enterprises to improve the sustainability in production and operation.

5. Conclusions

In order to help the medium and small-size manufacturing enterprises better achieve the purpose of sustainable development, this paper combines the triple bottom line theory with the dual resource constrained flexible job shop scheduling problem. In this research, a MPEA/SG based algorithm is designed, and the model we proposed and the effectiveness of this algorithm are all validated by the case study. This research provides a framework of implement sustainable development for the decision makers in the manufacturing enterprises. Future research can consider multi-product categories and production scheduling in uncertain environments.

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