Research Article

An Effective Hybrid Multiobjective Flexible Job Shop Scheduling Problem Based on Improved Genetic Algorithm

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Multiobjective Flexible Job Shop Scheduling Problem (MO-FJSP) is a scheduling problem used in manufacturing sectors to use energy efficiently and thrifty. The scheduling problem aims to increase productivity and reduce energy consumption via a mathematical model. With this paper, an effective genetic algorithm is proposed for MO-FJSP based on maximum completion time, total machine load, and bottleneck machine load. The solution method utilizes a hybrid multiobjective genetic algorithm. A combination of global selection and fast selection is used for initialization and obtaining a uniformly distributed initial population. The cross-variance operator is adaptively improved to enhance the searching in the population. Following that an elite retention mechanism is designed to address the possible limitations of the elite strategy in maintaining population diversity. As a result, an improved harmonic search algorithm is introduced to improve the quality of individuals in the elite pool. The proposed hybrid method is implemented in MATLAB R2018a. Tests were conducted using the benchmark Kacem test set, the BR data data set, and with the actual production cases. The algorithm succeeded in achieving 13 nondominated solutions in the initial 20 runs. Moreover, the method obtains the optimal value criterion for the solution accuracy factor. As a whole, results of the evaluation testify that the proposed method can be used to solve the MO-FJSP with high accuracy and fast convergence. The method also provides feasible and effective scheduling solutions for the decision-makers in actual production. Based on the promising results obtained, it is deduced that the method has a wide applicability range particularly in manufacturing sector.

1. Introduction

With every passing day, awareness about environmental issues and lack of energy sources, new ways are searched out to efficiently use energy in the manufacturing of machines and mechanical units [1]. For energy-efficient production processes, job-shop scheduling is been suggested by the researchers [2–4]. The traditional approaches of Job Shop Problems (JSP) [5] were all about minimizing the makespan. MO-FJSP on the other hand deals with the selection of operations together with influencing the sequence of operations [1]. Various scheduling approaches have also been proposed for productive utilization of resources. For instance, Shopfloor production scheduling is an effective scheduling method that can be used for effective and optimization as well. The rational scheduling method for the production plans in the manufacturing process is another useful approach. The method plays a key role in improving the productivity, resource utilization, and cost reduction of enterprises. Nevertheless, the Flexible Job Shop Problem (FJSP) introduces new decision content into the traditional job-scheduling problem. The additional content supported in FJSP includes the solution of two subproblems. One of the subproblems is to select the appropriate machine for each process. The second subproblem is to determine the start and end processing time of the processes, a more complex NP-hard problem [6].

After nearly 30 years of exploration, the research of FJSP has achieved fruitful results. Until now, different metaheuristic algorithms have been successfully applied in practical scheduling problems. For instance, the genetic algorithm (GA) [7], particle swarm algorithm [8], forbidden search algorithm [9], and simulated annealing algorithm [10] are some of the extensively used algorithms. With
advancement in research, the multiobjective flexible job shop scheduling (MO-FJSP) appeared to be more in line with the production reality. Hence, MO-FJSP has become a pressing problem to be solved. Since last decade, new algorithms have been proposed to offer more options and to conveniently solve MO-FJSP. Meng, Champion et al. [11] proposed a hybrid artificial bee colony algorithm. The algorithm utilizes different search methods in three distinct stages: hiring bee, following bee, and detecting bee. In addition, a forbidden search algorithm is introduced to improve the probability of obtaining the optimal solution. Saha et al. [16] works on assignment rules and three process sequencing rules. Saha algorithm employs a strategy of mixing two machine to generate a high-performance initialization population. For the purpose, a GA is proposed by Wang et al. [15] to shrink the maximum workpiece completion time. Key motive of the research works is to shrink the maximum workpiece completion time. For the purpose, a GA is proposed by Wang et al. [15] to generate a high-performance initialization population. The algorithm employs a strategy of mixing two machine assignment rules and three process sequencing rules. The two-population algorithm of Nawaz Ripon [16] works on picking two subpopulations to optimize two subproblems, machine allocation, and process sequencing sequences.

Similarly, Chen et al. [17] designed a machine-selection method for the effective solution of machine load balancing. The algorithm follows three selection strategies (global, local, and random) to generate solution. Huang et al. [18] defined a new transformation method based on differential evolutionary (DE) algorithm for solving FJSP. To improve search performance, the method combines DE with critical path local search technique. In a similar research work [19], the critical path local search strategy is used besides the shuffled frog leading algorithm (SFLA). The method promises for the improved convergence performance of SFLA. In Osaba et al.’s study [20], a discrete harmony search (DHS) algorithm is suggested to encode the machine selection and process ranking subproblems. The designed algorithm transforms a continuous harmonic vector into two discrete vectors. The strategy of VNS is proposed in the literature [21] to solve the single-objective FJSP.

To summarize, there are two general approaches to multiobjective optimization problems: the a priori method and the posteriori method. Both of the methods deal with resolving possible conflicts involved in multiple objectives. The a priori method generally uses the experience to form a single objective by linear weighting of multiple objectives. However, fewer solutions can be obtained using this type of method. The method fails to reflect the trade-off between different objectives [3]. Moreover, it is difficult to precisely determine weights of each objective. Enough experience is required to solve optimization problems; however, the true Pareto front is nonconvex [3] in the aggregation-based approach. From the in-depth analysis of the literature, it is clear the priori methods are basically used to transform the multiobjective into a single objective by weighting. Although a posteriori method may offer multiple solutions, the method lacks problem-based local search. Hence, the obtained solutions are somehow unreasonable and cannot guarantee a set of optimal solutions. It is why such algorithms do not effectively balance the global search and local development [3].

Details of some of the standard approaches in the realm of job shop problem are presented in Table 1.

3. Multiflexible Job Shop Scheduling Problem Model

A multi-FJSP is the extension of the tradition JSP which allows multiple operations to be processed by a set of machines. The problem is about assigning an operation to a machine by ordering the operations on the machines. Key focus of the MJSP is to attain minimum makespan of all the operations. It is a sort of NP-hard problem to effectively deal the two subproblems: assignment and the scheduling.

3.1. Problem Description. In the actual flexible shop production, there exist parallel machine flexibility, worker flexibility and process flexibility at the same time. This paper proposed a novel approach for MO-FJSP that is summarized in the following steps. (1) Multiple workpieces are processed on multiple machines by multiple workers belonging to each
### 3.2. Symbol Definition

The notation used in the model is defined as follows:

- $n$ indicates the total number of workpieces
- $m$ indicates the total number of machines
- $u$ indicates the total number of worker skill levels
- $i$, $e$ are the subscripts of the workpiece, where $j_1$, $j_e$ are the $i$th and $e$th workpieces to be machined
- $L_0$, $L_e$ are the number of priority levels contained in the artifacts, $j_1$, $j_e$, respectively
- $j, f$ are the priority subscripts, whereas $F_{ij}, F_{ij-1}, F_{il}$ are the priorities of the $j$th, $j-1$th (i.e., the previous layer of the $j$th layer) and last layers of artifact $j_i$; $F_{ef}$ is the priority of the $f$th layer of the artifact
- $k_{ij}, k_{ij-1}, k_{il}, k_{ef}$ is the number of processes competing with priority $k_{ij}, k_{ij-1}, k_{il}, k_{ef}$
- $k, q, g$ are the process subscripts where $O_{ijk}$ and $O_{ijq}$ are the $k$th and $q$th processes with priority $k_{ij}, O_{ilg}$ is the $g$th process in priority $F_{il}$, $q$th process in priority $O_{ij-1}$, $K_{ij-1}$ is the $g$th process in priority $O_{efg}$

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### 3.3. Model Establishment

The mathematical model of multiflexible job shop scheduling problem is given as follows:

**Minimize:**

\[
\begin{align*}
C_{\text{max}} &= \max_{1 \leq i \leq n}(C_i) = \max_{1 \leq i \leq n}\left(\max_{1 \leq k \leq K_{ij}}(C_{ilk})\right), \\
E &= \sum_{p=1}^{m} \sum_{i=1}^{n} \sum_{j=1}^{k_i} \sum_{k=1}^{N_s} \sum_{l=1}^{g} \sum_{s=1}^{n} X_{ijkp} x_{ijkns} \cdot P_{f_{ijkp}},
\end{align*}
\]

where:

- $C_{\text{max}}$ is the maximum completion time
- $C_{\text{mean}}$ is the average completion time
- $E$ is the total energy consumption
3.3.2. Processing Time Constraint

\[
\min C_{\text{mean}} = \frac{\sum_{i=1}^{n} C_i}{n} = \frac{\sum_{i=1}^{n} \max_{s \in S, K_i}(C_{i,s,k})}{n}
\]  

Equations (1) to (3) are the optimization objectives: (1) represents the minimized maximum completion time; (2) represents the minimized total energy consumption; and (3) represents the minimized average completion time. The model has the following constraints.

3.3.1. Processing Resource Constraints

\[
\sum_{p=1}^{m} \left( sT_{efg} - eT_{ijk} \right)x_{efgsv}
\]

\[
x_{ijksv} \geq 0 \forall i, j, k, e, f, s, v: i, e = 1, 2, \ldots, n; s = 1n2, \ldots, u; v = 1, 2, \ldots, N_s; j = 1, 2, \ldots, L_i; f = 1, 2, \ldots, L_j k = 1, 2, \ldots, K_{ij}; g = 1, 2, \ldots, K_{ef},
\]  

\[
\sum_{s=1}^{N_s} \sum_{v=1}^{N_v} \left( sT_{efg} - eT_{ijk} \right)x_{efgsv}
\]

\[
x_{ijksv} \geq 0 \forall i, j, k, e, f, s, v: i, e = 1, 2, \ldots, n; s = 1n2, \ldots, u; v = 1, 2, \ldots, N_s; j = 1, 2, \ldots, L_i; f = 1, 2, \ldots, L_j k = 1, 2, \ldots, K_{ij}; g = 1, 2, \ldots, K_{ef},
\]

Equation (6) and (7) ensure that one worker or one machine can be involved in processing only one process at the same time.

3.3.2. Processing Time Constraint

\[
eT_{ijk} - sT_{ijk} = \sum_{p=0}^{m} \sum_{s=1}^{N_s} \sum_{v=1}^{N_v} x_{ijk}x_{ijksv}
\]

\[
\forall i, j, k: i = 1, 2, \ldots, n; j = 1, 2, \ldots, L_i; k = 1, 2, \ldots, K_{ij}.
\]  

Equation (8) represents the relationship between process start time and completion time.

(3) Workpiece completeness constraint and transportation time constraint

\[
sT_{uf} - eT_{ijk} = \sum_{p=0}^{m} \sum_{r=0}^{n} x_{ijk}x_{uf},
\]

\[
\text{trans} T_{pr} \geq 0 \forall i, j, e, k, f: i = 1, 2, \ldots, n; j = 1, 2, \ldots, L_i; e = 1, 2, \ldots, L_i k = 1, 2, \ldots, K_{ij}; f = 1, 2, \ldots, K_{ef}.
\]  

Equation (9) represents the transport time required for a workpiece to be processed in only one process at the same moment while ensuring its transfer from one machine to another.

3.3.3. Priority Constraint

\[
sT_{ijk} \geq \max_{1 \leq q \leq K_{ij}} (eT_{ij-1q}),
\]

\[
\forall i, j: i = 1, 2, \ldots, n; j = 1, 2 \cdots L_i.
\]

Equation (10) ensures that the workpiece with the highest priority is machined first.

3.4. Code. A four-chromosome integer code can be used for the proposed MO-FJSP. One of the chromosome codes the machine and the other chromosome codes the worker assignment, as shown in Figure 2. The process O122 is selected and assigned to the machine number three and worker number three. It should be noted that the worker serial number is uniform for all workers, for example, workers W_{11}, W_{12} and W_{21}, W_{22} in two skill levels will be renumbered as W_1, W_2, W_3, W_4.

Two chromosomes encode process ordering is followed in the algorithm. From the two chromosomes, the first chromosome has genes that are both subscripts of the artifacts. The second chromosome has genes that are distorted integers from 1 to the total number of processes, as shown in
Mechanical selection
Worker assignment

\[
\begin{array}{cccccccc}
O_{111} & O_{121} & O_{122} & O_{131} & O_{132} & O_{211} & O_{212} & O_{221} & O_{222} \\
1 & 2 & 3 & 1 & 4 & 2 & 1 & 2 & 4 \\
1 & 3 & 3 & 2 & 4 & 3 & 4 & 1 & 2 \\
\end{array}
\]

Figure 2: Machine and worker coding.

Figure 3. In Figure 3, the same artifacts in the chromosomes of process order 1 are divided into priority levels by sequential constraints, as shown in Figure 4. Each priority level in Figure 4 contains multiple processes. The processes in each priority level are sorted by the integer size of the corresponding position of the chromosome of Process Order 2 (see Figure 3). The sorting process is shown in Figure 5. The scheduling schemes obtained from the four-chromosome coding and decoding meets the constraints of the model.

For the characteristics of the problem and heuristic encoding, a variational crossover operator is proposed. Detail of the process is given as followed.

3.4.1. Variation Operator. To carry out the evolutionary process, multiobjective algorithms rely on the use of variation operators. In the proposed method, a single-point mutation of one to multiple positions is used for machine-selected and worker-assigned chromosomes. The position swap technique is followed for chromosomes of process order 1. Four types of variable neighborhood search are adopted for the chromosome equal to the probability of process ordering 2. The neighborhood search variables followed in the algorithm are the swap, insertion, reversal of reverse order, and the disruption of swap [11].

3.4.2. Crossover Arithmetic. The crossover arithmetic operator is used to linearly combines the two parent chromosomes. In the proposed method, individuals of the parents were paired into different pairs. The pairs include selection of gene positions, exchange of genes on the machine-selected and worker-assigned chromosomes in the parent individuals. Furthermore, the pairs also include comparison of the artifact numbers of the chromosomes of process order 1 in the parent individuals and the selection of genes at other positions. The purpose of the paring is to complement the parents so that the total number of artifact numbers on the chromosomes remained the same after the exchange of genes. For the chromosomes of process order 2, equal probability position-based crossover (PBX) and linear order crossover (LOX) were used [11].

4. Optimization Algorithm

Optimization algorithm is the problem of discovering a set of inputs to an objective function to maximum or minimum the function evaluation. Some state-of-the-arts optimization algorithms are discussed in the following subsections.

4.1. Invasive Tumor Growth Optimization Algorithm. Invasive tumor growth optimization (ITGO) is a novel population intelligent optimization algorithm proposed by Wei et al. [12] in 2015. The algorithm is significantly more advantageous than the intelligent algorithms, continuous optimization problems [12], data clustering problems [13], and cloud computing task scheduling problems [14]. ITGO works on the simulation of tumor cells. The algorithm analyzes the solution of the problem of growing cells (Pcell), invading cells (Icell), dormant cells (Qcell), dead cells (Dcell), and so on. Moreover, the fitness value is assimilated to the nutrient concentration. In the algorithm, the cells will move toward the direction of higher nutrient concentration. Among the cells, the Icell is the most active one that takes up part of the search task and then all the tasks by jumping out of the local optimal solution. The Pcell takes up most of the search work, whereas the Qcell slowly executes the search strategy. The Dcell is formed by the decay of the dormant cells and releases the occupied computational resources once it completes its task. The various cells can be transformed into each other.

4.2. NSGA-II Algorithm. The nondominated Sorting Genetic Algorithm (NSGA) II makes the use of fast nondominated sorting (FNDS) method to classify individuals in the population into different nondominated ranks (NDR). The algorithm calculates the crowding distance between individuals NDRs. Next, individual filtering is performed based on NDR and crowding distance. In the multiobjective optimization problem with three or more objectives, the ranking method based on crowding distance is not obvious. To resolve the issue, Huang et al. [27, 28] suggested the reference-point-based method (RPBM) and NSGAIII. However, NSGAIII encounters the problem of excessive number of solutions while dealing with high dispersion problems. The problem of excessive number of solutions in the optimal NDR may be resolved at the later stage that will adversely affect further screening.

4.3. Multiobjective Invasive Tumor Growth Optimization Algorithm. In this paper, we propose a multiobjective invasive tumor growth optimization algorithm. Schematic of the algorithm is shown in Figure 6. The MOITGO is utilized along with the FNDS and RPBM-based selection methods and NSGAIII. The RPBM reference points are generated using Das and Dennis’s method [29]. In MOITGO, “division” refers to the replication of one original cell into another cell type while “transformation” refers to the change of cell type. A Pcell that remains unchanged during the growth
cycle may fall into the local optimal solution. Thus allowing Pcell to divide into an Icell and prevents the algorithm from falling into the solution. In the proposed method, the cell growth and invasion methods are redesigned according to the discrete characteristics of MO-FJSP, as shown in Figures 7 and 8, respectively.

5. Experiments and Analysis of Results

In order to verify the feasibility, effectiveness, and practicality of the proposed MO-FJSP solution method, standard algorithms were selected for the evaluation. The actual production cases for testing were derived from the widely acceptable algorithms including the Kacem test set [14] (8 × 8 (P-FJSP), 10 × 10 (T-FJSP), 15 × 10 (T-FJSP)), the BRdata data set [27] (MK01-MK10), and the BRdata data set [27] (MK01-MK10). The algorithm is programmed using MATLAB R2018a. For the implementation and evaluation a laptop, with CPU Intel i7-4558U running at 2.80 GHz, having 4 GB of RAM, and Windows 7 operating system, was used. The test objective functions were performed according to equations (1) to (3) presented in Section 1.2. The parameters set used in the proposed method includes total number of iterations, population size, crossover probability range (0.4, 0.8), variation probability range (0.01, 0.2), number of iterations of the harmonic search algorithm, and probability of fine-tuning the harmonic memory bank.

5.1. Experimental Setup. In order to systematically assess the proposed method from different perspectives, the following experiments were performed.

5.1.1. Experiment-1. The first experiment was conducted to compare the proposed method with the noninferior solutions of NSGA-II. After each 20 runs, results of the algorithms were compared in terms of maximum completion time and minimum under the BRdata data set. The results obtained are shown in Table 2.

As shown in Table 2, both the algorithms achieved promising results. Performance of the methods (the proposed and NSGA-II) are better than the Brandimarte’s method. Unlike our proposed method, quality of non-inferior solutions obtained by NSGA-II decreases with the increase of the problem size. For the problem MK02–MK10, the noninferior solutions obtained by our method are better than those obtained by NSGA-II. Moreover, the results of 20 operations do not fluctuate considerably. This shows good stability in the quality of solutions. The iterative process and the distribution of noninferior solutions for a certain run of the MK01 problem are compared.

5.1.2. Experiment-2. Under the Kacem test set results, the proposed method is compared with the hybrid artificial bee colony algorithm (ABC + TS). The ABC algorithm proposed by Champion Meng is considered to one of the state-of-the-art algorithm in the literature. Moreover, the results were also compared with the other cutting-edge algorithms namely the variable neighborhood weed optimization algorithm (IWO + VNS) proposed by Lei Cao, and the hybrid algorithm of local approximation and control genetic algorithm (AL + CGA) proposed by Kacem. Outcomes of the comparison are shown in Table 3.

It is clear from Table 3, that IWO + VNS obtained more noninferior solutions for the Kacem 8 × 8 problem. However, none of the algorithms reached the optimal value for the rest of the problems. Unlike others, the method proposed in this paper obtained the optimal value criterion in terms of solution accuracy. The number of nondominated solutions obtained by the proposed method is also not inferior to the other algorithms.

5.1.3. Experiment-3. In order to robustly assess the practicality of our method, it is evaluated by solving practical problems. This experiment intends to measure the judge the algorithm in scheduling case of an automotive wiring harness manufacturing enterprise. The production process of an automotive wire harness includes wire laying,
crimping, internal linking, subassembly and final assembly, and so on. Taking a wire harness with 6 branches as an example, the 6 subassembly branches in the corresponding process were treated to be 6 workpieces. Each of the workpiece $J_1, J_3, J_4$, contains 4 processes with process sequence number: 1, 2, 3, and 4. The workpiece $J_2, J_5, J_6$ contains 3 processes with process sequence numbers 1, 2, and 4. The output of the product was deemed to be 50 pieces. The production data of wire harness products are shown in Table 4.

As presented in the actual production data in Table 4, the NSGA-II and our proposed method were used for the scheduling solution. The results were also compared with the traditional manual scheduling method. Outcomes of the scheduling methods in solving the actual problem are compared and shown in Table 5.

From the facts presented in Table 5, it is clear that the manual scheduling method relies more on human than the two intelligent scheduling algorithms. As the scheduling and production processing time is longer, therefore, the scheduling effect is poorer. Our proposed method has obvious advantages over the NSGA-II in terms of production processing time and the number of noninferior solutions despite the fact that the scheduling time was slightly longer. The automotive wiring harness company can select the appropriate solution from the obtained noninferior solutions to guide the production.

![Figure 7](image-url)
In summary, the method proposed in this paper has high solution accuracy and fast convergence. The algorithm carries a commendable global and local search capability. The method achieves optimal results on the selected benchmark instances of different scales and actual production cases. Moreover, the algorithm has better adaptability and robustness than the other contemporary algorithms. From the promising results obtained in the evaluation, it is proved that the proposed method is feasible and effective for solving MO-FJSP. Keeping in view

![Figure 8: The process of cells invasion.](image)

| Problem type | $n \times m$ | $T$ | Brandimarte method (min) | NSGA-II (min) | Our method (min) |
|--------------|--------------|-----|------------------------|--------------|-----------------|
| MKO1         | $10 \times 6$ | 55  | $f_{1}$               | $f_{2}$      | $f_{3}$         |
| MKO2         | $10 \times 6$ | 58  | $f_{1}$               | $f_{2}$      | $f_{3}$         |
| MKO3         | $15 \times 8$ | 150 | $f_{1}$               | $f_{2}$      | $f_{3}$         |
| MKO4         | $15 \times 4$ | 90  | $f_{1}$               | $f_{2}$      | $f_{3}$         |
| MKO5         | $10 \times 15$ | 106 | $f_{1}$               | $f_{2}$      | $f_{3}$         |
| MKO6         | $20 \times 5$ | 150 | $f_{1}$               | $f_{2}$      | $f_{3}$         |
| MKO7         | $20 \times 20$ | 100 | $f_{1}$               | $f_{2}$      | $f_{3}$         |
| MKO8         | $20 \times 10$ | 225 | $f_{1}$               | $f_{2}$      | $f_{3}$         |
applicability of the algorithm, the method is suitable to be used in related domains.

6. Conclusion and Future Strategy

In this paper, the population initialization, cross-variation method and elite retention strategy of NSGA-II were improved. The method introduced intends to effectively ensure the population diversity and improve the global and local search capability of the algorithm. The hybrid multiobjective genetic algorithm of the method utilizes NSGA-II as the main and acoustic search as the supplement algorithm. The advantages of both the algorithms are fully combined in one to improve the solution quality. The feasibility and effectiveness features of the algorithm were assessed for solving MO-FJSP. Experimentations were conducted with the standard algorithms: Kacem test set, BRdata data set, and actual production cases. Outcomes of the assessments reveal that the method proposed has better practical significance.

In future, it is planned to augment the method so that the algorithm should dynamically study its own characteristics in depth. This will enable the algorithm to explore the improvement strategies under different target requirements. By that way, the hybrid multiobjective genetic algorithm will continuously improve, the solution quality will be enhanced and efficiency of the algorithm will be increased desirably.

Data Availability

The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The author declares no financial and personal relationships with other people or organizations that can inappropriately influence this work.

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