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Review on flexible job shop scheduling

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Abstract: Flexible job shop scheduling problem (FJSP) is an NP-hard combinatorial optimisation problem, which has significant applications in the real world. Due to its complexity and significance, lots of attentions have been paid to tackle this problem. In this study, the existing solution methods for the FJSP in recent literature are classified into exact algorithms, heuristics and meta-heuristics, which are reviewed comprehensively. Moreover, the real-world applications of the FJSP are also introduced. Finally, the development trends of the manufacturing industry are analysed, and the future research opportunities of the FJSP are summarised in detail.

1 Introduction

Production scheduling is one of the most critical issues in manufacturing systems and has been extensively studied in the literature [1]. Production scheduling is concerned with allocating available production resources to tasks and deciding the sequence of operations so that all constraints are met and the optimisation objectives are optimised [2]. One of the most famous production scheduling problems is the job shop scheduling problem (JSP), which is NP-hard [3]. In the JSP, a set of jobs are to be processed on a finite machine set. According to its production routine, each job is processed on machines with given processing time, and each machine can process only one operation for each job [4]. Flexible JSP (FJSP) is an extension of the JSP, which is also NP-hard [5]. Different from the JSP, there exists a set of available machines to be selected for each operation in the FJSP, which increases the flexibility and complexity of scheduling [6]. Hence, the FJSP is more complex than JSP.

Since there are many significant applications of the FJSP in a series of real-world scenarios, this problem has attracted a lot of attention [4]. This paper briefly describes the FJSP, and reviews many existing solution methods for the problem in the recent literature. These solutions can be classified into three aspects, including exact algorithms, heuristics and meta-heuristics. Furthermore, this paper also presents future research trends and opportunities in detail.

The rest of the paper is organised as follows: Section 2 gives a brief description of the FJSP. Section 3 reviews various solution methods for the problem comprehensively. Section 4 surveys the real-world applications of the FJSP. Finally, Section 5 discusses the development trends and future research opportunities.

2 Problem description

The FJSP can be illustrated as follows [6]: A set of n jobs $J = \{J_1, J_2, \dots, J_n\}$ are to be processed on a set of m machines $M = \{M_1, M_2, \dots, M_m\}$. The operation permutation $\{O_{i1}, O_{i2}, \dots, O_{ip_i}\}$ for each job J_i is processed according to a given sequence. Each operation can be processed on several machines in M. The FJSP is to determine the most appropriate machine for each operation (called machine selection) and the sequence of the operations on machines (called operation sequencing). The optimisation objective of the FJSP is to minimise some indicators, e.g. makespan, maximum tardiness and total flow time. Moreover, there are some assumptions and constraints for the FJSP, which can be listed as follows:

(i) All machines are available at time zero.
(ii) All jobs are available after release dates.
(iii) Each operation can only be processed on one machine at a time.
(iv) Each machine can only perform one operation at a time.
(v) Each operation cannot be interrupted during the processing process.
(vi) There are no precedence constrains among operations of different jobs, because the jobs are independent of each other.
(vii) For each job, the sequence of operations is predefined.

According to whether all operations can be processed on all machines, The FJSP can be classified into two categories, i.e. total FJSP (T-FJSP) and partial FJSP (P-FJSP) [7], which are described as follows: (i) T-FJSP. Each operation can be processed on all machines; (ii) P-FJSP. There is at least one operation that can only be processed on all machines. The T-FJSP can be considered as a special case of the P-FJSP.

The FJSP with the kinds of optimisation objectives has been widely studied in the literature. Some optimisation objectives are summarised in Table 1. The first column indicates the notations of the optimisation objectives, the second column describes corresponding objective functions, the third column explains the meaning of the notations, the fourth column gives the interpretation and the fifth column provides the corresponding literatures.

3 Solution methods for FJSP

More than one hundred recent papers are reviewed in this paper, which includes many variants of the classical FJSP. Some variants are quite different from the classical FJSP while more suitable for practical production environments. This section presents a comprehensive survey of various solution techniques for the classical FJSP with its variants. The main solution techniques are classified into three categories, i.e. exact algorithms, heuristics and meta-heuristics.

3.1 Exact algorithms

In the previous literature, researchers presented some exact algorithms to solve the FJSP, most of which are formulated by integer linear programming (ILP) or mixed ILP (MILP) models.

Table 1 Optimisation objectives of the FJSP

Notation	Description	Meaning	Interpretation	References
$C_{\max}$	$\max_j (C_j)$	makespan or maximum completion time	cost of a schedule depends on how long the entire set of jobs has finished processing	Pezzella and Ciaschetti [5] and Zhang *et al.* [8]
$T_{\max}$	$\max_j (T_j)$	maximum tardiness	maximum difference between the completion time and the due date of a single job	Baykasoglu [9]
T_t	$\sum T_j$	total tardiness	positive difference between the completion time and the due date of all jobs and there is no reward for early jobs and only penalties incurred for late jobs	Scrich *et al.* [10] and Brandimarte [11]
$\overline{T}$	$(\sum T_j)/n$	mean tardiness	average difference between the completion time and the due date of a single job	Tay and Ho [12] and Chen *et al.* [13]
$L_{\max}$	$\max_j (L_j)$	maximum lateness	check how well the due dates are respected, and there is a positive reward for completing a job early	Chen *et al.* [14]
I_t	$\sum I_j$	total idle time	difference between running time and processing time of all machines	Chen *et al.* [13]
F_t	$\sum F_j$	total flow time	time that all jobs spent in the shop	Baykasoglu [9]
$\overline{F}$	$(\sum F_j)/n$	mean flow time	average time a single job spent in the shop	Tay and Ho [12] and Chen *et al.* [13]
$W_{\max}$	$\max_j (W_j)$	maximum workload	maximum working time among all machines	Xia and Wu [1] and Zhang *et al.* [15]
W_t	$\sum W_j$	total workload	total working time on all machines	Kacem *et al.* [7] and Gao *et al.* [16]
O_t	$\sum O_j$	total operation cost	cost value of all operations	Frutos *et al.* [17] and Rabiee *et al.* [18]
E_t	$\sum E_j$	total energy consumption	energy consumption of the whole production process	Mokhtari and Hasani [19] and Lei *et al.* [20]

Stecke [21] defined five production planning problems for a flexible manufacturing system (FMS) and addressed the grouping and loading problems specifically. These two problems are first formulated in detail as non-linear 0-1 mixed integer programs. Sawik [22] formulated a multi-level ILP model for FMS. The hierarchical decision structure is designed with part type selection, machine loading, part input sequencing and operation scheduling. de Werra and Widmer [23] presented some ILP models for considering FMS with the following types of tool management: the system works in time periods whose durations are fixed or not; and tools are loaded on the machines at the beginning of each time period and stay there for the whole time period. Jiang and Hsiao [24] used 0-1 integer programming for FMS considering the operational scheduling problem and the determination of production routing with alternate process plans simultaneously. The approach of mathematical programming generates the optimal schedule, rather than near optimal schedule or a better schedule, to meet the selected criterion. In order to optimise the allocation of workloads between a job shop and an FMS, Tetzlaff and Pesch [25] proposed some non-linear optimisation models. These models allow to optimise performance parameters such as throughput, work-in-process inventory, utilisation, and production lead time. Gomes *et al.* [26] formulated a new ILP model to schedule the flexible job shop, operating on a make-to-order basis. The model considers groups of parallel homogeneous machines, limited intermediate buffers and negligible set-up effects; then they used a commercial MILP software to solve it. Torabi *et al.* [27] developed a new mixed-integer non-linear program which simultaneously determines machine allocation, sequencing, lot-sizing and scheduling decisions to addresses the common cycle multi-product lot-scheduling problem in deterministic flexible job shops where the planning horizon is finite and fixed by management. Özgüven *et al.* [28] developed a MILP-1 model for FJSPs, and compared to an alternative model (Model F) to verify its superiority. Furthermore, they modified MILP-1 to give rise to MILP-2 for the same problem. Elazeem *et al.* [29] proposed a mathematical model for FJSP, where the objective is to minimise the makespan. Then they introduced its dual problem (Abdou's problem), the optimal value of which is a lower bound for the objective value of the primal problem. Özgüven *et al.*[30] formulated two mixed-integer goal programming (MIGP) models for FJSP, which covers process plan flexibility and separable/non-separable sequence dependent setup times in addition to routing flexibility. In the first model (Model A) the sequence-dependent setup times are non-separable, and in the second one (Model B) separable. Jahromi and Tavakkoli-Moghaddam [31] presented a novel 0-1 ILP model considering the problem of dynamic machine-tool selection and operation allocation with part and tool movement policies in FMS. The objective of this model is to determine a machine-tool combination for each operation of the part type by minimising production costs. Roshanaei *et al.*[32] developed two novel effective position-based and sequence-based MILP models to deal with the FJSP to minimise makespan. Birgin *et al.* [33] proposed a MILP model for an extended version of the FJSP. The extension allows the precedence between operations of a job to be given by an arbitrary directed acyclic graph rather than a linear order.

Also, to formulate ILP models, some researchers employed branch and bound approach to solve FJSP. Berrada and Stecke [34] first discussed a non-linear integer mathematical programming formulation of the loading problem in FMS. This problem involves assigning the machine tools, operations and associated cutting tools. They used a branch-and-bound approach to balance the workload on all machines. Kim and Yano [35] developed an efficient branch-and-bound algorithm for the FMS, which allocates operations to machine groups to maximise throughput while satisfying tool or component storage constraints. Zhou *et al.* [36] constructed Petri net models for the FMS, and used a branch-and-bound algorithm to obtain the optimal schedule of the problem. Lloyd *et al.* [37] proposed an optimum scheduling algorithm for FMS using Petri net modelling and modified branch-and-bound search. The scheduling algorithm implemented a global search of the reachability tree and obtained the optimum makespan through a modified branch-and-bound search.

To minimise makespan for the FJSP with work centres, Hansmann *et al.* [38] derived a MILP model to represent the problem and further proposed a branch-and-bound method to solve it. Moreover, some researchers have also considered the multi-objective FJSPs (MOFJSPs). Gomes *et al.* [39] presented a MILP mode for the FJSP considering the re-entrant process (multiple visits to the same machine group) and the final assembly stage simultaneously. The optimisation objective is minimising a weighted sum of order earliness, order tardiness and in-process inventory. Gran *et al.* [40] formulated a MIGP model to solve the FJSP with the objectives of minimising makespan and the total machining time. They presented an optimal production job shop scheduling strategy based on the solution model and adopted a preemptive goal programming approach by Microsoft Excel Solver Add-Ins to solve this problem.

3.2 Heuristics

Many heuristics, including dispatching rules, have been applied to deal with the FJSP. For instance, Shanker and Tzen [41] compared heuristic methods with the exact mixed-integer programming from the perspective of minimising the workload and balancing the sequence of jobs in a random FMS. A simulation model was proposed to evaluate the system performance with four dispatching rules, i.e. FIFO, SPT, LPT and MOPR. Chang *et al.* [42] developed and evaluated a beam search heuristic method for addressing the FMS. The proposed beam search method is more sophisticated than traditional dispatching rules. However, it is computationally feasible and achieved better performance. Ro and Kim [43] developed heuristics for solving the FMS with the constrain of system utilisation. O'keefe and Kasirajan [44] combined nine dispatching rules with four next station selection rules to investigate a large dedicated FMS. Xiong *et al.* [45] presented a hybrid search algorithm for scheduling FMS. The hybrid heuristic search algorithm is combined with the execution of the timed Petri nets to search for an optimal or near-optimal and deadlock-fee schedule. Jeong and Kim [46] proposed a real-time scheduling method which used simulation and dispatching rules for FMS. Mati *et al.* [47] used an integrated greedy heuristic to handle the FJSP with more than two jobs. Scrich *et al.* [10] developed two heuristics, a hierarchical procedure and a multiple start procedure, based on tabu search (TS) for solving FJSP. The procedures use dispatching rules to obtain an initial solution and then search for improved solutions in neighbourhoods generated by the critical paths of the jobs in a disjunctive graph representation. In the work of Mejía and Odrey [48], a new Petri net-based algorithm, named Beam A* Search, was presented. This algorithm selectively expands portions of a Petri net reachability graph to find a near optimal schedule. Alvarez-Valdés *et al.* [49] presented a heuristic to minimise the total cost corresponding to the completion times of jobs for the FJSP in a glass factory. Pitts and Ventura [50] proposed a two-stage algorithm to solve production routing and job sequencing within a flexible manufacturing cell. During the construction phase, two heuristics are utilised to generate an initial feasible sequence and an initial manufacturing makespan solution. Fattahi *et al.* [51] developed two heuristics, including integrated and hierarchical approaches to solving the FJSP. Six different hybrid searching structures depending on the used searching approach and heuristics were proposed. To cope with the complexities for FMS, Huang *et al.* [52] presented a hybrid heuristic search strategy, which combines the heuristic A* strategy with the DF strategy based on the execution of the Petri nets. The search scheme can invoke quicker termination conditions, and the quality of the search result is controllable. Wang *et al.* [53] proposed a filtered-beam-search-based (FBSB) heuristic algorithm to obtain sub-optimal schedules for FJSP with multiple objectives, i.e. minimising the makespan, the total workload of machines and the workload of the most loaded machines. The FBSB utilised dispatching rules-based heuristics and explored the search space intelligently to avoid useless search, which may enhance the search speed. Tay and Ho [12] proposed effective composite dispatching rules discovered from the genetic programming approach to solve the MOFJSP. Wang and Yu [54] developed the FBSB heuristic algorithm to deal with the variant FJSP problem with maintenance activities. To schedule FMS efficiently, Lee and Lee [55] proposed some new heuristic functions for A* algorithm. In terms of the objective of minimising the makespan, the proposed heuristic functions are usually more efficient than the previous functions in the required number of states and computation time. Nie *et al.* [56] studied a heuristic to solve the dynamic FJSP with job release dates. Based on harmony search and large neighbourhood search, Yuan and Xu [57] designed a hybrid two-stage search heuristic for solving the large-scale FJSP with makespan criterion. Ziaee [58] proposed an efficient heuristic based on a constructive procedure to obtain high-quality schedules for FJSP with the objective of minimising makespan. Afterward, Ziaee [59] developed a heuristic based on a constructive procedure to further deal with the FJSP including the scheduling of jobs in a distributed manufacturing environment. Calleja and Pastor [60] presented a dispatching algorithm with some priority dispatching rules to solve a real-world case of the FJSP with transfer batches. The objective is to minimise the average tardiness of production orders. Baruwa and Piera [61] presented a simulation-optimisation approach employing an anytime search method to optimise FMS. The proposed approach combines the column search method with backtracking that offers an anytime behaviour in a time-constrained environment. Afterward, Baruwa *et al.* [62] proposed an anytime heuristic search method to solve the DL-free scheduling problem of FMS with shared resources. The algorithm has been tested extensively on five different cases of DL-prone situations in realistic manufacturing systems. Gao *et al.* [63] presented four ensembles of heuristics to schedule the FJSP with new job insertion. The objectives are to minimise the makespan, an average of earliness and tardiness (E/T), maximum machine workload and total machine workload. Pérez and Raupp [64] proposed a new hierarchical heuristic to solve the MOFJSPs. The heuristic is an adaptation of Newton's method for solving continuous multi-objective unconstrained optimisation problems. For the FJSP considering minimising the total weighted tardiness, Sobeyko and Mönch [65] devised an iterative local search approach, and hybridised the shifting bottleneck heuristic with the iterative local search and variable neighbourhood search to obtain high-quality solutions quickly. Miguel *et al.* [66] proposed a heuristic method based on TS for solving the FJSP with the constrain of lot streaming. Shahgholi Zadeh *et al.* [67] designed a heuristic algorithm model for solving a dynamic FJSP to minimise makespan. This model involves the setup time of machines in the dynamic re-scheduling. Ortíz *et al.* [68] proposed a dispatching rule to solve practical FJSP. As one of the heuristic algorithm, the effectiveness of their proposed dispatching rule is higher than the related swarm intelligence algorithms in practical textile manufacturing. Teymourifar *et al.* [69] devised an effective dispatching rule to solve a dynamic FJSP with limited buffer. A right shift heuristic and least waiting time heuristic were effectively proposed for solving the stochastic condition of machine breakdown. Ozturk *et al.* [70] extracted a hybrid priority scheduling rule though gene expression programming. The proposed scheduling rule is combined with the cellular system for solving the multi-objective and dynamic FJSP. Based on a case study of FJSP, Bekkar *et al.* [71] proposed two greedy heuristics based on an iterated insertion technique to solve the problem with the constraint of transportation time between machines.

3.3 Meta-heuristics

3.3.1 Population-based meta-heuristics: The population-based meta-heuristics have been widely applied for solving the FJSP, where the genetic algorithm (GA) perhaps is the most widely utilised. The GA has been used to effectively solve not only the single-objective FJSP, but also the MOFJSP.

Frist, the solution methods for FJSP with a single objective are introduced, and makespan is the most common objective. Many meta-heuristic algorithms based on GA have been proposed to solve the problem. For instance, Pezzella and Ciaschetti [5] presented a GA for the FJSP. The algorithm integrates different strategies for generating the initial population, selecting the individuals for reproduction and reproducing new solutions. Kacem *et al.* [7] presented two approaches to solve the FJSP. The first one is the localisation, and the second one is GA. They applied genetic manipulations to enhance the quality of solutions. Gao *et al.* [16] developed a hybrid GA with variable neighbourhood descent to address the FJSP with three objectives: minimising makespan, maximal machine workload and total workload. An innovative two-vector representation scheme and an effective decoding method were proposed to interpret each chromosome into an active schedule. Zhang *et al.* [8] proposed an effective GA for solving the FJSP to minimise makespan. In the algorithm, an improved chromosome representation scheme is proposed and an effective decoding method interpreting each chromosome into a feasible active schedule is designed. Based on GA and grouping GA, Chen *et al.* [13] developed a scheduling algorithm for solving FJSP with the objectives of minimising multiple performance measures including total tardiness, total machine idle time, and makespan. Chang *et al.* [72] proposed a GA embed the Taguchi method behind mating to increase the effectiveness for solving the FJSP. Nouri *et al.* [73] proposed a hybridisation of two meta-heuristics within a holonic multi-agent model for solving the FJSP. The scheduler agent applies a neighbourhood-based GA for global exploration, and the cluster agent uses a local search technique. Jiang and Du [74] presented an improved GA, where a new initialisation method is adopted to improve the quality of the initial population and accelerate the convergence speed of the algorithm. For the same problem, Huang *et al.* [75] also proposed an improved GA, where two effective crossover methods and two mutation methods are designed. Later, they proposed another improved GA with a new adaptive probability of crossover and mutation in the mating process [76], so that the convergence rate is greatly improved. Then, Driss *et al.* [77] proposed a GA to solve the FJSP to minimise makespan. A new chromosome representation is used to conveniently represent the solution and special crossover and mutation operators were designed correspondingly. Purnomo [78] developed an improved GA with a knowledge-based system to solve the FJSP. Some heuristics are embedded in the GA for improving the algorithm performance. Morinaga *et al.* [79] developed a GA which takes advantage of knowledge included in heuristic dispatching rules to solve the FJSP. Machine selection and job selection are performed at once to relieve insufficient search of the solution space. To improve the exploitation ability of the GA, many researchers combine the GA with local search heuristics. Li and Gao [80] proposed a hybrid algorithm which hybridises the GA and TS for the FJSP. Gu *et al.* [81] presented an improved simulated annealing GA (ISAGA) to solve FJSP. In the ISAGA, an X conditional cloud generator in cloud model theory is used to generate the mutation probability and simulated annealing (SA) operation is designed for the variability of results. Zhang *et al.* [82] developed a variable neighbourhood search (VNS) based on GA to deal with the FJSP. In their proposed algorithm, some simple local search methods are used to balance exploration and exploitation. Ma *et al.* [83] proposed a memetic algorithm (MA) to solve the FJSP. The MA is a hybrid GA combined with two efficient local searches to exploit information in the search region. Cinar *et al.* [84] proposed a GA with priority-based representation for solving the FJSP. The priority of each operation is represented by a gene on the chromosome. To obtain improved solutions, iterated local search (ILS) is embedded in their algorithm.

Other objectives are also considered in the paper, e.g. tardiness. Brandimarte [11] proposed a hierarchical TS algorithm for FJSP considering makespan and total weighted tardiness. Hierarchical strategies are designed for scheduling problems, and the TS is used to cope with different hierarchical memory levels. Türkyılmaz and Bulkan [85] developed a new algorithm hybridising the GA and VNS to solve the FJSP to minimise total tardiness. Parallel-executed VNS algorithm is used in the elitist selection phase to minimise execution time. For the same objective, Kaweegitbundit and Eguchi [86] proposed a GA that incorporates heuristic rules to solve it. Combinations of five job selection and five machine selection heuristics are embedded in this algorithm.

Moreover, researchers have designed many GA-based approaches to solve MOFJSPs. The basic MOFJSP can be classified by different objective combinations. Frutos *et al.* [17] proposed an MA based on non-dominated sorted GA II (NSGA)-II to solve the MOFJSP. A local search procedure (SA) is added to the genetic stage to avoid the algorithm getting trapped in a local minimum. Yuan and Xu [87] proposed a new MA based on NSGA-II for this problem with the objectives to minimise the makespan, total workload, and critical workload. In their proposed algorithm, a hierarchical strategy is used to handle the three objectives. An optimisation algorithm according to a variety of population genetic-variable neighbourhood search was proposed by Liang *et al.* [88] to solve the MOFJSP. The new algorithm aims at minimising the makespan, obtaining the smallest machine maximum load and the smallest total machine minimum loads. Meanwhile, the new algorithm improves the inherent defects of poor local search ability, premature convergence and longtime calculation compared with traditional GA. Then, Ren *et al.* [89] proposed an immune GA (IGA) which combines the artificial immune mechanism and GA to solve the MOFJSP with the objectives of maximising due time satisfaction and minimising the total processing costs. Morinaga *et al.* [90] presented a GA using TS strategy for the MOFJSP with weighted tardiness, setup worker load balance, and work-in-process as objectives. Liang *et al.* [91] developed an MA in the frame of NSGA-II to deal with FJSP. On the basis of NSGA-II, an improving elite strategy based on circular crowding distance is designed to increase the diversity of population distribution, and avoid the algorithm trapping in a local optimum. Recently, Deng *et al.* [92] presented a bee evolutionary guiding non-dominated sorting GA II for the MOFJSP with the objectives to minimise the maximal completion time, the workload of the most loaded machine, and the total workload of all machines. Zhang *et al.* [93] developed a multi-population GA to solve the MOFJSP whose objectives is minimising the longest makespan of work pieces, the load of each machine, and the total machine load. Ghasemi and Farzan [94] presented a classical weighted sum method and NSGA-II to solve the FJSP with multiple objectives: minimising the completion time of jobs and maximising machine employment. To generate Pareto-fronts, the algorithm uses the mechanism of variable weights and random selection to change directions in search spaces. Teymourifar *et al.* [95] proposed two modified NSGA-II algorithms to solve the MOFJSP. The neighbourhood structures in the algorithms are designed to create better offspring during the evolutionary process.

Recently, there are many variants of FJSP shown in the literature. Tayebi Araghi *et al.* [96] proposed a genetic variable neighbourhood search to solve the FJSP with sequence-dependent set-up times (SDST), learning effect and deterioration in jobs. In the same year, Jalilvand-Nejad and Fattahi [97] studied an FJSP with cyclic jobs. In the problem, jobs must be delivered in determined batch sizes with definite time intervals. They proposed GA and SA to solve this problem, respectively, and the result shows that GA achieves better performance than SA. To deal with the FJSP considering lot-sizing and SDST, Rohaninejad *et al.* [98] proposed a novel mixed-integer programming model based on big bucket time, and developed a new hybrid algorithm combining GA, particle swarm optimisation (PSO) and a local search heuristic. Rey *et al.* [99] proposed two meta-heuristics, i.e. GA and PSO, to solve the flexible job-shop just-in-time scheduling problem. The scheduling objective of just-in-time production is translated into the minimisation of the mean-square due to date deviation, quadratically penalising inventory (earliness) costs and backlogging (tardiness) costs. To handle a complex JSP with characteristics of re-entrant and flexible, Zhang and Wu [100] proposed an improved GA with a comprehensive search mechanism to overcome the contradiction between convergence rate and convergence accuracy. Li *et al.* [101] proposed an improved GA to solve the FJSP with small batch customisation. The standard GA is improved by designing a genetic operator based on dynamic procedure encoding, reserving the optimal individual and meeting requirements of FJSP. Chang and Liu [102] proposed a hybrid GA with a novel encoding mechanism to solve the distributed FJSP. Lu *et al.* [103] proposed an improved GA to solve the same problem. In the algorithm, they developed a 1D-to-3D decoding method to convert a 1D chromosome into a 3D solution. Azzouz *et al.* [104] proposed a self-adaptive evolutionary algorithm which combined GA with VNS and ILS to solve the FJSP with SDST and learning effects. Elgendy *et al.* [105] designed a modified GA which incorporates the traditional procedures of GA with a repair strategy to optimise the makespan of dynamic FJSP. Chen and Li [106] proposed a modified meta-heuristic algorithm based on GA to solve the FJSP with different varieties and small batches. An initialisation operation associated with a time matrix is devised to accelerate the convergence speed and the generation gap coefficient is applied to guarantee the survival rate of superior offspring. For solving the dynamic FJSP considering machine failure, urgent job arrival, and job damage as disruptions, Wang *et al.* [107] proposed a dynamic rescheduling method based on variable interval rescheduling strategy. Meanwhile, they proposed an improved GA to solve the dynamic FJSP with the objective of minimising makespan. Peng *et al.* [108]

presented a GA to solve a double resource FJSP. Both machines and workers are considered in the process of job shop scheduling. In this algorithm, a new well designed three-layer chromosome encoding method is adopted and some effective crossover and mutation operators are designed. For the MOFJSP under random machine breakdown, Ahmadi *et al.* [109] applied two evolutionary algorithms, i.e. NSGA-II and NRGA, to improve makespan and stability simultaneously. For bi-objective FJSP under stochastic processing time, Yang *et al.* [110] proposed a NSGA-II to solve it with consideration of the completion time and the total energy consumption. Wang *et al.* [111] proposed an effective MA which combines NSGA-II with a local search method for simultaneously optimising fuzzy makespan, average agreement index and minimal agreement index. A variable neighbourhood local search is specially developed to enhance the exploitation ability. Since the importance of environmental protection in recent years, carbon emissions and energy consumption are considered in MOFJSP. Jiang *et al.* [112] proposed a modified NSGA-II to solve the MOFJSP considering energy consumption. Yin *et al.* [113] proposed a new low-carbon flexible job-shop mathematical scheduling model and addressed a multi-objective GA (MOGA) based on a simplex lattice design to solve this problem. For the MOFJSP with the objectives of minimising total carbon footprint and total late work criterion, Piroozfard *et al.* [114] proposed an improved MOGA and compared it with NSGA-II and the strength Pareto evolutionary algorithm to verify its superiority. For solving the FJSP with energy-saving measures, Wu and Sun [115] considered when to turn-on/off machines and which speed level to choose as two measures to save energy. They proposed an energy consumption model to compute the energy consumption for a machine in different states and developed a NSGA to solve this problem. Zhang *et al.* [116] proposed a low-carbon scheduling model for FJSP. For quantifying the carbon emission of different scheduling plans, they gave three carbon efficiency indicators to estimate the carbon emission of parts and machines, and proposed a hybrid NSGA-II for solving this problem. Azzouz *et al.* [117] proposed a hybrid algorithm based on GA and VNS to solve the FJSP considering sequence-dependent setup times with two kinds of the objective function, makespan and bi-criteria objective function.

In addition to GA, other population-based meta-heuristics have also been applied to solve the FJSP. The criterion of makespan is considered the most. For instance, Marzouki and Driss [118] proposed a new multi-agent model based on the meta-heuristic chemical reaction optimisation (CRO) to solve the FJSP to minimise makespan. Afterwards, they hybridised the CRO with TS to deal with the same problem [119]. Yang [120] proposed an effective modified biogeography-based optimisation algorithm with machine-based shifting to solve the FJSP with makespan minimisation. Then, Lin [121] developed a hybrid biogeography-based optimisation algorithm for solving the FJSP with the makespan criterion. An insertion-based local search heuristic is incorporated into the BBO to modify the mutation operator to balance the exploration and exploitation abilities. PSO was also often used to solve the FJSP with makespan minimisation in recent years. Xia and Wu [1] developed an easily implemented hybrid approach combining PSO and SA for the FJSP. The results obtained from the computational study have shown that the proposed algorithm is viable and effective for the MOFJSP, especially for problems on a large scale. Zhang *et al.* [15] combined a PSO algorithm and a TS algorithm to solve the MOFJSP with the objectives of minimising makespan, maximal machine workload and total workload of machines. Singh and Mahapatra [122] proposed a quantum-behaved PSO for solving the FJSP, which overcomes the drawback of PSO easily getting trapped at a local optimum. Muthiah *et al.* [123] proposed a hybridisation of PSO and the artificial bee colony (ABC) to solve the FJSP to minimise makespan. Yi *et al.* [124] proposed an effective MA, which is a combination of TS and GA for the FJSP to minimise the makespan. Phu-ang and Thammano [125] proposed a new MA based on marriage in honey bees optimisation algorithm for solving FJSP. The algorithm employs the incorporation of SA blended with a set of heuristics to enhance its local search capability. Ge *et al.* [126] proposed an efficient artificial fish swarm model with an estimation of distribution for the FJSP to minimise the makespan. A pre-principle and a post-principle arranging mechanism in this algorithm are designed to enhance the diversity of the population. Wang and Yi [127] designed a bacterial foraging algorithm to solve the FJSP. An improved adaptive step and a stop condition are designed to solve the problems of local optimisation and prematurity. To overcome the disadvantage of low efficiency in convergence speed, Wu and Wu [128] developed an elitist quantum-inspired evolutionary algorithm to solve the FJSP. Xu *et al.* [129] proposed an improved bat algorithm to solve the FJSP with a new encoding strategy. Wang *et al.* [130] developed an improved ant colony optimisation with high computational efficiency to solve the FJSP with makespan criterion. An improved hybrid immune algorithm with parallelism and adaptability was proposed by Liang *et al.* [131] to solve the FJSP with makespan as objective, and an SA is embedded in this hybrid algorithm to avoid the local optimisation. Buddala and Mahapatra [132] proposed a teaching–learning-based optimisation (TLBO) to solve the FJSP based on the integrated approach with the objective to minimise makespan. A new local search technique followed by a mutation strategy is integrated into the TLBO to avoid being trapped at the local optimum. Jiang and Zhang [133] proposed a grey wolf optimisation (GWO) algorithm to deal with the FJSP with the objective of minimising makespan. In the GWO, an adaptive mutation method is designed to keep the population diversity and avoid premature convergence. Recently, Gaham *et al.* [134] proposed an effective operations permutation based discrete harmony search approach for tackling the FJSP with makespan criterion.

Some population-based meta-heuristics have also been used to solve the MOFJSP with multiple different criteria. For example, Rabiee *et al.* [18] proposed four multi-objective, Pareto-based, meta-heuristic optimisation methods to solve the MOFJSP with the objectives of minimising makespan and total operation costs. Xue *et al.* [135] proposed a quantum immune algorithm based on the quantum and immune principles to solve the MOFJSP whose objectives are makespan, the workload of machines and workload of the critical machine. Ma *et al.* [136] proposed an MA based on the non-dominated neighbour immune algorithm to tackle the FJSP whose objectives are minimising makespan and total operation cost. Gong *et al.* [137] designed an MA with a well-designed chromosome encoding/decoding method to solve the MOFJSP whose objective is to minimise the maximum completion time, the maximum workload of machines and the total workload of all machines. Mekni and Fayech [138] used a modified invasive weed optimisation algorithm to solve the MOFJSP with three criteria to minimise the makespan, the total workload of machines and the workload of the critical machine. Karthikeyan *et al.* [139] developed a hybrid discrete firefly algorithm combined with local search to solve the MOFJSP with objectives of minimising the maximum completion time, the workload of the critical machine and the total workload of all machines. As with solving the traditional FJSP with makespan criterion, PSO is also often used to solve MOFJSP. For example, Kamble *et al.* [140] proposed a hybrid algorithm based on PSO and SA to solve the FJSP with five objectives to be minimised simultaneously, i.e. makespan, maximal machine workload, total workload, machine idle time and total tardiness. Huang *et al.* [141] proposed a multi-objective PSO (MOPSO) integrating with VNS for solving the MOFJSP with three criteria: the makespan, the total workload and the critical machine workload. Then, they mixed the MOPSO and SA with VNS to solve the same problem and obtained a better solution [142]. Zeng and Wang [143] hybridised a chaotic SA with particle swarm improved artificial immune algorithm for solving the MOFJSP with considerations for makespan and processing cost. Zhu *et al.* [144] proposed a modified bat algorithm to solve the MOFJSP. In this algorithm, five neighbourhood structures are hybridised with the BA to improve the searching ability.

Meanwhile, there are also many meta-heuristics applied to non-traditional FJSPs. For instance, Rossi [145] proposed an ant colony optimisation (ACO) algorithm based on a disjunctive graph model to deal with the FJSP with sequence-dependent setup and transportation time. An effective TLBO was proposed by Xu *et al.* [146] to solve the FJSP with fuzzy processing time. A bi-phase crossover scheme based on the teaching–learning mechanism and special local search operators are incorporated into the search framework of TLBO to balance the exploration and exploitation capabilities. Liu *et al.* [147] simplified a dynamic FJSP with fuzzy processing time as a traditional static FJSP with fuzzy processing time and proposed estimation of distribution algorithm to solve the post-transforming problem. Gao *et al.* [148] proposed a two-stage ABC algorithm to solve the FJSP with new job insertion for scheduling and rescheduling. Furthermore, Gao *et al.* [149] addressed an improved ABC algorithm to solve the FJSP with fuzzy processing time whose objective is to minimise the maximum fuzzy completion time and the maximum fuzzy machine workload. Meng *et al.* [150] presented a hybrid ABC (hyABC) algorithm to minimise the total flowtime for the FJSP with overlapping in operations. In the proposed hyABC, a dynamic scheme is introduced to fine-tune the search scope adaptively. Zheng and Wang [151] developed a knowledge-guided fruit fly optimisation algorithm with a new encoding scheme to solve the dual-resource constrained flexible job-shop scheduling problem with makespan minimisation. Liu *et al.* [152] formulated a multi-objective optimisation model based on FJSP aimed at minimising carbon footprints of all products and makespan, and designed a hybrid fruit fly optimisation algorithm to solve the proposed model. Zandieh *et al.* [153] considered the FJSP with condition-based maintenance and proposed an improved imperialist competitive algorithm combined with SA to solve this problem. Nouiri *et al.* [154] developed a two-stage PSO to solve the FJSP under machine breakdowns assuming that there is only one breakdown. Jamrus *et al.* [155] developed a hybrid approach integrating PSO with a Cauchy distribution and genetic operators (HPSO + GA) for solving the FJSP by finding a job sequence that minimises the maximum flow time with uncertain processing time. Singh *et al.* [156] proposed a multi-objective framework based on quantum PSO to solve the FJSP with random machine breakdown. Reddy *et al.* [157] proposed a new evolutionary based multi-objective TLBO combined with a local search technique to solve the FJSP with machines breakdown as a real-time event. Zhang and Wong [158] proposed an approach named HMA, a combination of multi-agent system negotiation and ACO, to solve FJSP under a dynamic environment. Azzouz *et al.* [159] proposed a self-adaptive hybrid algorithm with a new adaptation strategy based on similarity function and archiving process to solve the FJSP where sequence dependent setup times are considered. Aiming at minimising the total cost for the FJSP with controllable processing times, Mokhtari and Dadgar [160] developed a scatter search to find the best trade-off between processing cost and delay cost. Lu *et al.* [161] proposed a new multi-objective discrete virus optimisation algorithm for solving the FJSP with controllable processing times, and the objectives are minimizing both the makespan and the total additional resource consumption. Mokhtari and Hasani [19] developed an enhanced evolutionary algorithm incorporated with the global criterion to solve the MOFJSP with three objective functions: minimising total completion time, maximising the total availability of the system, and minimising the total energy cost of both production and maintenance operations. Lei *et al.* [20] developed a shuffled frog-leaping algorithm based on a three-string coding approach to solving the FJSP with the objectives of minimising the workload balance and total energy consumption. For solving the multi-objective stochastic FJSP, Shen *et al.* [162] proposed a modified multi-objective evolutionary algorithm based on decomposition, which makes the elitists kept in an archive and preserved in the child generation.

3.3.2 Single solution-based meta-heuristics: Besides population-based meta-heuristics, single solution-based meta-heuristics have also often been utilised to solve FJSPs, where SA is one of the popular ones. For instance, Baykasoglu [9] presented a meta-heuristic based on SA to solve the FJSP considering makespan, mean flow time, number of tardy jobs, maximum tardiness and total machine idle time. The approach makes use of the grammars from linguistics to represent the data of FJSP and the dispatching rules for operation sequencing. Khalife *et al.* [163] developed an effective SA for solving the MOFJSP with overlapping in operations. The evaluation criteria of the MOFJSP are makespan, total machine work loading time and critical machine work loading time. Shivasankaran *et al.* [164] proposed a new hybrid non-dominated sorting SA to solve the MOFJSP with the objectives of minimising makespan, critical machine workload, the total workload of the machines and total operating cost. The critical or incapable machine is eliminated by sorting all the non-dominant operations, which effectively reduce the computational time complexity of the algorithm. Then, Shivasankaran *et al.* [165] devised a hybrid sorting immune SA algorithm to solve the FJSP. A critical machine isolating strategy in this algorithm is used to improve the local search ability. Bożejko *et al.* [166] developed double paralyzed SA algorithms, including fine-grained vector processing, multiple walk-multi core processing to deal with the cyclic FJSP. Kaplanoğlu [167] developed a SA with an object-oriented (OO) approach for solving the MOFJSP. The OO approach can reduce the complexity of problem coding by using UML class diagrams.

In addition to SA, many other single solution-based meta-heuristics have also been applied to solve the FJSP. For example, Chen *et al.* [14] developed a scheduling algorithm, including two major modules: the machine selection module and the operation scheduling module, for solving the FJSP. The objectives of the algorithm are maximising on-time delivery rate and minimising the makespan, the maximum lateness, and the average tardiness. Karimi *et al.* [168] combined the VNS algorithm with a knowledge module to solve the FJSP to minimise makespan. The VNS part searches good solutions from the solution space and obtains the knowledge from the knowledge module, which makes the search process more efficient. Meanwhile, Lei and Guo [169] devised a VNS algorithm, composed of two neighbourhood SAs and a restarting mechanism, for solving the dual-resource constrained FJSP to optimise makespan. Vilcot and Billaut [170] studied two kinds of TS algorithms to minimise the makespan, maximum lateness and total tardiness simultaneously for the MOFJSP. Jia and Hu [171] showed a novel path-relinking TS for solving the multi-objective FJSP, whose objective is minimising makespan, total workload of all machines (in terms of processing time) and the workload of the most-loaded machine. Rajkumar *et al.* [172] proposed a greedy randomised adaptive SA algorithm to solve the FJSP with limited resource constraints. The objectives of the algorithm are to minimise makespan, maximum workload and total workload. Yulianty and Ma'ruf [173] proposed an algorithm for solving the FJSP considering controllable processing time and expected downtime by using a predictive approach.

4 Real-world applications

The FJSP has important applications in the real world. Several complicated realistic problems have been modelled as the FJSP in literature. Meanwhile, a series of solution methods have been specially developed to cope with these problems; some applications are listed in this section. Li *et al.* [174] proposed a modified GA, which has been verified in the scheduling decision support system for the seamless steel tubes production in Baoshan Iron & Steel Complex. Chen *et al.* [13] studied a new algorithm based on GA and Grouping GA in a real weapon production factory. Gomes [26] presented a new ILP model to solve the FJSP, which is derived from a discrete part and make-to-order manufacturing industry. Birgin *et al.* [33] studied an extended FJSP, where the precedence between operations of a job is given by an arbitrary directed cyclic graph instead of a linear order. They formulated a new MILP model for FJSP and used CPLEX to solve the instances inspired by the real data from a printing industry.

Hansmann *et al.* [38] studied a MILP model of the FJSP with work centers which exist in rail car maintenance, and used a branch-and-bound procedure to solve this model. Grobler *et al.* [175] developed four kinds of PSO-based heuristics for solving the MOFJSP with sequence-dependent setup times, auxiliary resources and machine down time. Comparison results on real customer data indicated that the priority-based PSO algorithm performs better than the existing rule-based algorithms commonly used for this problem. For the FJSP from the printing and boarding industry, two TS algorithms were proposed to obtain a set of non-dominated solutions [170]. Alvarez-Valdes *et al.* [49] devised a heuristic to solve the FJSP existed in a glass factory, which produced a lot of manufactured glass objects in a complex process. Calleja and Pastor [60] proposed a dispatching algorithm for the FJSP with transfer batches, which is arisen from a realistic auto parts manufacturing plant. Tanev *et al.* [176] presented a hybrid evolutionary algorithm by combining the priority-dispatching rules with the GA to schedule a case of FJSP, the customers' orders in the factories of plastic injection machines. Hosseinabadi *et al.* [177] devised a gravitational emulation local search algorithm to deal with the multi-objective dynamic FJSP in small and medium enterprises.

5 Development trends and future research opportunities

5.1 Development trends

With the rapid development of economy and society, the manufacturing industry has encountered more and more opportunities and challenges, e.g. mass customisation, virtual enterprise, distribution manufacturing and green manufacturing have attracted more and more attention. Intelligent manufacturing is the main theme as the result of the demands of Industry 4.0. The advanced technologies such as big data and artificial intelligence can provide powerful tools for coping with these challenges, which can further guide new development trends of the manufacturing industry. Various tasks of FJSP have increased substantially among the rapid development of the manufacturing industry.

5.2 Future research opportunities

5.2.1 New mode of FJSP: Mass customisation, providing customers with products and services for specific needs, will result in new requirements of the FJSP modes, such as dynamic scheduling, online scheduling, real-time scheduling and reverse scheduling. To meet the realistic requirements, new optimisation objectives should be considered, e.g. robustness, satisfaction degree, and system stability. This will result in the FJSP with more than three objectives, i.e. many-objective FJSP, which should also be paid more attention.

5.2.2 New model of FJSP: The personalised needs are becoming increasingly complex, which make the practical production environments (e.g. the realistic production conditions and customer demands) more and more complicated. These complicated factors should be considered in the model of FJSP. Moreover, more constraints such as production resources, buffer size, due date, batch size and cost, should be taken into account in the FJSP.

5.2.3 New solution methods for FJSP: With the development of data analysis and artificial intelligence (including machine learning, deep learning and so on), data-driven modelling methods provide new and effective ways to solve the engineering optimisation problem which is difficult to establish mathematical model. The joint data-model driven solution methods can be employed to solve complicated FJSP. For example, the energy consumption model of FJSP can be formulated based on the theoretical energy consumption model and carbon emission statuses of the actual workshops. Big data and artificial intelligence technologies can extract effective information from the production data to guide the model establishment. Moreover, these technologies can also be employed to predict the occurrence of dynamic events (e.g. machine breakdown, new order arrival), and solve the dynamic FJSP.

Also, more research can focus on solving the FJSP by new intelligent optimisation algorithms. Due to the complexity of the actual production environments, it may be difficult to be fully simulated. Therefore, some surrogate-model-based optimisation methods can be used to solve the FJSP in actual production environments to obtain a better schedule in a shorter time.

5.2.4 FJSPs under the new manufacturing form: Worldwide corporate restructuring inflows significantly affect manufacturing modes. Distributed manufacturing has become a late-mode of production with the increasing popularity of cooperative production among companies and mergers between enterprises. Distributed manufacturing can make full use of the resources of multiple enterprises or factories, and achieve rapid production at a reasonable cost by implementing the rational allocation, combination and sharing of resources. With the progress of science and technology, the individualised and diversified development of consumer demands promotes the diversification of commodity supply. To satisfy the demands of consumers with low cost, high quality, personalisation and rapid response, mass-customised production models have emerged.

Moreover, to cope with new opportunities in the market, enterprises with different resources and advantages have established a mutually beneficial enterprise alliance based on a data network to share technology and information. Virtual enterprise, a mode of production and operation, provides a new way for manufacturing enterprises to quickly respond to market changes and establish competitive advantages.

With the changes in manufacturing mode, the scheduling models and solution methods also need to be changed accordingly. To solve the FJSP under the new manufacturing model, new scheduling models should be established under the background of cooperative production between different companies or factories, and new solution methods should be devised to optimise scheduling indicators and enable enterprises to produce high-quality products with lower cost and risk.

5.2.5 New applications of the FJSP: It is necessary to develop Cyber-Physical System (CPS) [178] or digital twin [179] driven scheduling methods for the FJSP and further adopt them to handle practical problems. CPS integrates advanced information and automatic control technology including sensing, computing, communication and control etc., to construct a complex system which combines the actual production environment with production data closely. This system can implement on-demand response, fast iteration and dynamic optimisation of resource allocation and operation assignment in the workshop.

Digital twin constructs a virtual entity and system that can represent the actual production workshop in virtual (information) space. Researchers can read various real-time parameters of the control system, construct visual remote monitoring and collect historical data, analyse the health of the production system, and use artificial intelligence technology to achieve production trend prediction. Based on the production information, the strategies of equipment maintenance and resource management can be optimised to reduce and avoid the losses caused by unexpected downtime. These new technologies can help to apply the theories and methods of FJSP much better.

5.2.6 Integrated with other systems: Recently, the integration and collaboration of the shop scheduling system with logistics, production environment, human and equipment has become a new research trend. In the existing researches, aiming at small batch production, the combination of shop scheduling system and process planning system has been effectively used to optimise the selection of process routes, shorten the production cycle, reduce the rework rate and improve the flexibility of manufacturing system.

With the increasing complexity of the production environment, the shop scheduling system also needs to track logistics information in real time, which helps workers grasp the current product transportation status, control and analyse the production environment. Meanwhile, track logistics information in real time can instruct operators to follow the standard procedures, monitor the operation, and output the performance of equipment to ensure the stability of the production process.

Therefore, the integration of job shop scheduling system and other systems can timely deal with abnormal conditions in production process and further globally control the production environment of the workshop.

5.2.7 Closed-loop of scheduling decision: Open-loop scheduling means that once the scheduling strategy is made, the whole scheduling process is carried out in strict accordance with the scheduling strategy, which cannot be adjusted according to the change of the actual production environment. In the environment where the production system can be accurately modelled, the open-loop scheduling strategy can achieve good performance. However, in the actual production environment, the scheduling plan and customer need often change, it is difficult to establish an accurate shop scheduling model. Aiming at these problems, open-loop scheduling strategy hardly guarantees effective scheduling performance, and lead to the utilisation deterioration of the resources in workshops. Closed-loop scheduling can dynamically adjust the scheduling scheme according to the real-time production status of the workshop to deal with the problems generated during the production process (e.g. new order arrival, machine breakdown etc.). Integrating big data, CPS, digital twin and other technologies, closed-loop scheduling can monitor the production situation of the workshop in real time. The real-time production data is used as a feedback signal to predict the uncertain events in the workshop, and precautions can be taken in advance to guarantee the stableness of production. Meanwhile, closed-loop scheduling can make full use of the resources in the workshop to availably balance machine loading and production efficiency.

5.2.8 Extensions of FJSP: Besides the FJSP, there also exists a large number of scheduling problems in other fields, e.g. enterprise management, transportation, aerospace, health care, and network communications. The existing mathematical model and solution methods for the FJSP can be extended to these scheduling problems, since there are similarities between them. For instance, in the logistics scheduling problem, products need to be assigned to different transport vehicles, which is similar to the FJSP where jobs need to be assigned to different machines. In the nurse scheduling problem, it is necessary to consider the degree of fatigue of the nurses so that they cannot continue to work night shifts, similarly to the consideration of the machine workload in the FJSP. Therefore, extending the mathematical model and solution methods of the FJSP to other scheduling problems will also be one of future research trends.

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