INTERNATIONAL TRANSACTIONS IN OPERATIONAL RESEARCH

WILEY

INTERNATIONAL TRANSACTIONS IN OPERATIONAL RESEARCH

Intl. Trans. in Op. Res. 23 (2016) 551–591
DOI: 10.1111/itor.12199

A research survey: review of flexible job shop scheduling techniques

Imran Ali Chaudhry[a] and Abid Ali Khan[b]

[a] *Department of Industrial Engineering, National University of Sciences & Technology (NUST), Islamabad, Pakistan*
[b] *Department of Aeronautics and Astronautics, Institute of Space Technology (IST), Islamabad, Pakistan*
E-mail: imran_chaudhry@yahoo.com [Chaudhry]; khanabid62@hotmail.com [Khan]

Received 16 October 2014; received in revised form 7 May 2015; accepted 9 July 2015

Abstract

In the last 25 years, extensive research has been carried out addressing the flexible job shop scheduling (JSS) problem. A variety of techniques ranging from exact methods to hybrid techniques have been used in this research. The paper aims at presenting the development of flexible JSS and a consolidated survey of various techniques that have been employed since 1990 for problem resolution. The paper comprises evaluation of publications and research methods used in various research papers. Finally, conclusions are drawn based on performed survey results.

Keywords: scheduling; flexible job shop; partial flexibility; total flexibility; heuristics; metaheuristics

1. Introduction

The last three decades have seen extensive development of efficient techniques to solve the flexible job shop scheduling problem (FJSSP). The scope and purpose of this paper is to present a survey of various techniques used for solving FJSSP using different objective functions. Numerous approaches have thus been investigated and these techniques are classified for ease of analysis.

The paper comprises the following major sections. The FJSSP is defined in Section 2. A summary of sources for the published papers and their year-wise distribution is presented in Section 3 and later a summary of various objective functions is given in Section 4. Section 5 gives a brief description of each technique used along with salient features of published work. Analysis and discussion of the survey results are presented in Section 6 and the paper concludes with a future research roadmap.

Published by John Wiley & Sons Ltd, 9600 Garsington Road, Oxford OX4 2DQ, UK and 350 Main St, Malden, MA02148, USA.

2. Flexible job shop scheduling problem

Job shop scheduling (JSSP) is a classical operations research problem that has been considered as a hard combinatorial optimization problem since the 1950s. In terms of computational complexity, JSSP is NP-hard in the strong sense (Garey and Johnson, 1979). Therefore, even for very small JSSP instances, an optimal solution cannot be guaranteed. In a job shop, every job may have a separate processing sequence. In the general JSSP, there is a finite set of n jobs to be processed on a finite set of m machines. Each job comprises a set of tasks that must be performed on a different machine and in specified processing times, in a given job-dependent order. A typical objective of this process is to minimize the total completion time required for all jobs or the makespan.

A flexible job shop problem (FJSSP) is an extension of the classical JSS problem that allows an operation to be processed by any machine from a given set of alternative machines. A general FJSSP may be formulated as follows:

(1) There is a set of n jobs to be processed on m machines.
(2) The set of m machines is noted as: $M = \{M_1, M_2, \ldots, M_m\}$.
(3) The job consists of a sequence of n_i operations as: $(O_{i,1}, O_{i,2}, \ldots, O_{i,ni})$.
(4) Each operation has to be performed to complete the job. The execution of each operation j of a job i ($O_{i,j}$) requires one machine out of a set of given machines $M_{i,j}$. The time of operation $O_{i,j}$ running on $M_{i,j}$ is $p_{i,j,k}$. Typically following assumptions are considered in a general FJSSP:
   (a) All machines are available at time $t = 0$.
   (b) All jobs are available at time $t = 0$.
   (c) Each operation can be processed by only one machine at a time.
   (d) There are no precedence constraints among the operations of different jobs; therefore jobs are independent from each other.
   (e) No pre-emption of operations is allowed, that is, an operation once started cannot be interrupted.
   (f) Transportation time of jobs between the machines and time to setup the machine for processing a particular operation are included in the processing time.

Classical JSS requires sequencing of operations on fixed machines, whereas in flexible JSS the assignment of an operation is not fixed in advance and can thus be processed on a set of capable machines. Therefore, in FJSSP we not only deal with sequencing, but also with assignment of operations to suitable machines (routing). FJSSP is therefore more complex than JSSP as it considers the determination of machine assignment for each operation. The scheduling of jobs in FJSSP can be categorized into following two subproblems.

1. A routing subproblem where we have to select a suitable machine among the available ones to process each operation.
2. A scheduling subproblem, where assigned operations are sequenced on all selected machines to obtain a feasible schedule that minimizes a predefined objective.

Based on flexibility, Kacem et al. (2002a) has classified the FJSSP into following two subproblems.

1. Total FJSSP: each operation can be processed on any of the "m" machines in the shop.
2. Partial FJSSP where some operations are only achievable on part of the available "m" machines in the shop.

Brucker and Schlie (1990) were the first to address FJSSP. Over the past 25 years, different methods and algorithms have been developed to solve this class of problem. Due to complexity of FJSSP, researchers have used a large number of techniques ranging from mathematical to various metaheuristics such as evolutionary algorithms (EAs), ant colony optimization (ACO), particle swarm optimization, and so on. This paper attempts to consolidate this research and present the findings.

3. Research survey results

A total of 404 distinct publications were found addressing the FJSSP. Some of the research papers presented more than one technique/algorithm to solve the problem that is categorized into 410 different applications. Selected time period of these research papers is between 1990 and February 2014. Articles were searched mainly on major databases such as SpringerLink, Science Direct, IEEE Xplore, Scopus, EBSCO, etc. and other web sources. All databases were searched for "flexible job shop" and "scheduling" in the title and keywords of the articles. The distribution of 404 papers in various sources is given in Table 1 and presented graphically in Fig. 1.

The references addressing the FJSSP has been categorized into five different types namely, journal, conference, book section, thesis, and report. The breakdown of 404 references into each of the mentioned reference category is tabulated in Table 1.

Due to large number of references available on the subject, this research work further concentrates on 191 journal papers only. The year-wise distribution of the 191 references is presented in Fig. 2. These 191 research papers address 197 different applications or techniques as some of these present more than one technique for problem resolution. Due to the practical nature of the problem, FJSSP has gained considerable importance during the last few years. It can be observed from Fig. 2 that relatively small number of papers addressed the problem in the first 10 years, which has grown tremendously from 2010 to 2013.

Table 1
Distribution of type of references

Type of reference	Total references
Book section	30
Conference paper	167
Journal article	191
Report	4
Thesis	12
Total	404

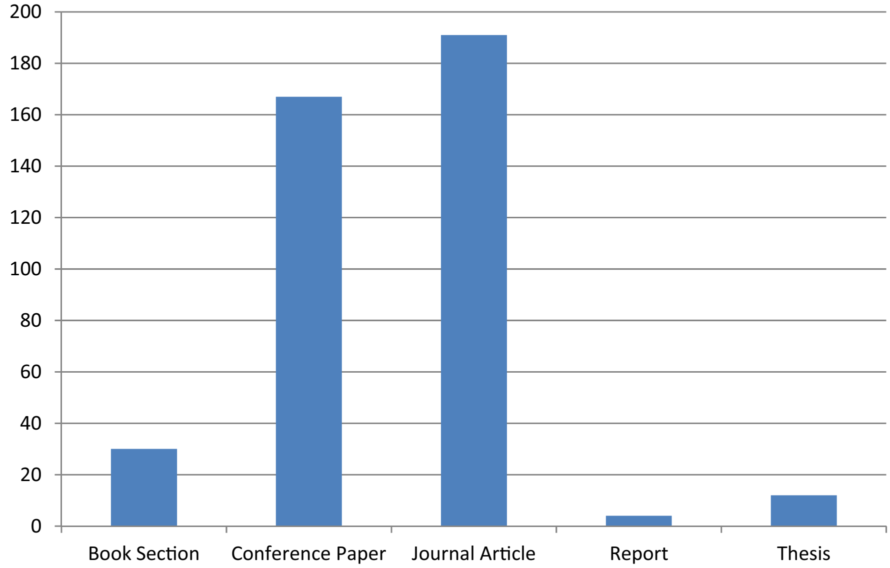

Fig. 1. Source distribution of reference papers.

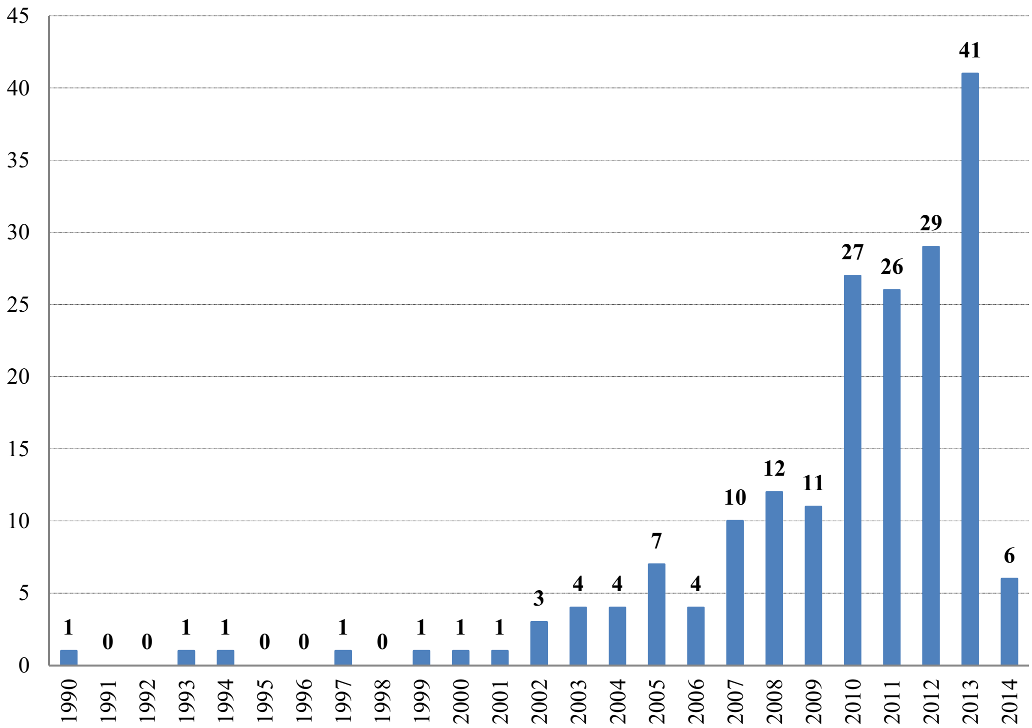

Fig. 2. Year-wise distribution of papers.

Table 2
Well-known performance measures

Objective function	Symbol	Type	Interpretation
Makespan or maximum completion time	C_{max}	Regular	The cost of a schedule depends on how long the processing system is devoted to the entire set of jobs
Mean completion time	$\bar{C}$	Regular	Average time taken to finish a single time
Maximum flow time	F_{max}	Regular	The longest time a job spends in the shop and schedule's cost is directly related to its longest job
Mean flow time	$\bar{F}$	Regular	Average time a single job spends in the shop and a schedule's cost is directly related to the average time it takes to process a single job
Total tardiness	T	Regular	Positive difference between the completion time and the due date of all jobs and is appropriate when early jobs bring no reward; there are only penalties incurred for late jobs
Average tardiness	$\bar{T}$	Regular	Average difference between the completion time and the due date of a single job
Total weighted tardiness	$\sum_{i=1}^{n} \alpha_i T_i$	Regular	Weighted measure that recognizes that some jobs are more important than others
Maximum lateness	L_{max}	Regular	Typically used to check how well the due dates are respected, and is appropriate when there is a positive reward for completing a job early; the earlier a job is completed, the larger is the reward
Number of tardy jobs	n_T	Regular	Number of jobs that are late
Total workload of machines	W_T		Represents the total working time on all machines
Critical machine workload	W_M		Represents most workload among all machines, that is the machine with the maximum workload

4. Objective functions used in FJSSP

Various researchers have addressed some of the commonly used objective functions that could be regular or irregular and these functions are tabulated in Table 2. An objective function is said to be regular if it is an increasing function, that is, it is always optimal to start (and complete) jobs as early as possible. French (1982) defines a regular measure (M) as a value to be minimized that can be expressed as a function of the job completion times (C_i) as given in relation 1. Thus:

$$M = f\left(C_1, C_2, \ldots, C_n\right) \quad (1)$$

Table 3
Survey results for various performance measures

Performance measure	Number of papers	Percentage
Makespan	88	44.67%
Minimum of makespan, workload of most loaded machine, total workload of machines	46	23.35%
Minimum of makespan and mean tardiness	5	2.54%
Minimum of makespan and production costs	4	2.03%
Total tardiness	3	1.52%
Minimum of mean tardiness	2	1.02%

and M increases only if at least one of the completion times increases as shown in relation 2. Thus if

$$M' = f\left(C_1', C_2', \ldots, C_n'\right) \tag{2}$$

then

$$M' > M \text{ only if } C_i' > C_i \quad \text{for at least one } i,\ 1 \leq i \leq n.$$

In case of regular measures of performance, it is always aimed to finish an activity earlier, rather than later. Examples include the average or maximum job completion times (makespan), flow times, lateness, or tardiness. However, in case of nonregular measures it may not be preferred to finish all jobs as early as possible. A nonregular performance measure is usually not a monotone function of the job completion times, for example, in a just-in-time environment, finishing jobs too early may represent excess WIP. Table 2 gives some of the well-known performance measures used in FJSSP.

Table 2 only gives the single performance measures, whereas multiobjective performance measures in FJSSP have been adequately addressed by a large number of researchers, whereby two or more performance measures tabulated in Table 2 are optimized simultaneously. Survey results revealed that a total of 55 different objective functions have been used in various publications out of which 49 measures were only used once, which implies that out of 197 research papers only six performance measures contributed to almost 75% of the published research work. Out of these six, only three were single performance measures while others were multiobjective performance measures. The survey results with respect to the six performance measures are given in Table 3, makespan came out to be the most widely used performance measure. In 88 research papers (44.67%) makespan was used as the sole objective function, while in another 78 papers (39.59%) makespan is used in combination with another objective function. The cumulative number of citations for these papers solely using makespan as the objective function is 4210, while when makespan is used in combination with other objective functions this number is noted to be 3482.

Table 4
Various techniques used to solve FJSSP

Technique	Number of papers	Percentage	Citations
Hybrid	69	35.03%	3572
EAs	47	23.86%	1940
Heuristic	19	9.64%	598
TS	12	6.09%	1297
Integer/linear programming	10	5.08%	233
PSO	8	4.06%	60
Miscellaneous techniques	7	3.55%	221
NS	6	3.05%	187
AIS	5	2.54%	110
Mathematical programming	4	2.03%	26
SA	4	2.03%	104
ACO	3	1.52%	117
GRASP	2	1.02%	32
ABC	1	0.51%	48

5. Review of techniques used for FJSSP

Based on the research papers collected, various techniques used in these research publications can be broadly categorized into 14 major categories. Brief review of each of the technique is given in the subsequent sections. These categories along with number of papers in each addressing the FJSSP problem are tabulated in Table 4. It can be seen that almost 59% of the papers used hybrid techniques or EAs.

5.1. Ant colony optimization

ACO algorithm is a probabilistic metaheuristic for solving combinatorial problems, which was introduced in 1990s. ACO is a member of the ant colony algorithms family in swarm intelligence methods. ACO is inspired by the pheromone trail laying behavior of real ant colonies whereby it mimics ants' social behaviors in finding shortest paths. ACO was initially developed by Dorigo (1992) to solve travelling salesman problem. The first known application of ACO to JSS is attributed to Colorni et al. (1994).

Rossi and Dini (2007) with 109 citations applied ACO in FJSSP with a sequence-dependent setup and transportation time, in addition operation lag times have also been taken into consideration. The authors develop an effective pheromone trail coding and tailored ant colony operators to minimize makespan. The algorithm has been tested with the standard benchmarks and problems. Xing et al. (2008) with 13 citations propose a double-layered ACO, where the upper layer assigns operations to machines while the lower layer schedules operations on each machine. The authors consider multiobjective performance measure where objective is to simultaneously minimize makespan, workload of most loaded machine, and total workload of machines. Experimental results suggest that the proposed algorithm is a feasible and effective approach for the multiobjective FJSSP. Huang et al. (2013) with eight citations considered minimization of the sum of weighted earliness and tardiness costs and proposed a two pheromone ACO approach for the FJSSP. The algorithm adds second pheromone group to the ant system in order to solve the scheduling problem faster. Computational results show that the proposed two pheromone ACO strategy yields better results as compared to traditional ACO and integer programming for a wide range of problems.

5.2. Artificial bee colony (ABC)

ABC algorithm is a swarm-based metaheuristic algorithm, introduced by Karaboga (2005) for optimization of numerical problems. The algorithm is motivated by the intelligent behavior of honey bees, that is, foraging behavior of honey bee colonies. The model consists of three essential components: employed, unemployed foraging bees, and food sources. The first two components, employed and unemployed foraging bees, search for rich food sources, the third component, close to their hive. The model also defines two leading modes of behavior that are necessary for self-organizing and collective intelligence: recruitment of foragers to rich food sources resulting in positive feedback and abandonment of poor sources by foragers causing negative feedback. The algorithm is specifically based on the model proposed by Tereshko and Loengarov (2005) for the foraging behavior of honey bee colonies. First reported instance of ABC algorithm application in JSS is attributed to Pansuwan et al. (2010).

Wang et al. (2012c) with 48 citations presented an effective ABC for solving the FJSSP with the criterion to minimize makespan. ABC algorithm stresses on the balance between global and local exploitation, thus special encoding and decoding schemes that are effective searching operators including hybrid initialization, crossover, mutation, local search, and population updating were well designed in the employed bee phase, onlooker bee phase, and scout bee phase. The proposed algorithm was capable to solve the FJSSP effectively, efficiently, and robustly, which has been demonstrated by simulation tests and comparisons to several existing algorithms.

5.3. Artificial immune system (AIS)

AIS are adaptive systems inspired by theoretical immunology and observed immune functions, principles, and models for applications to complex problem domains. The AISs are composed of intelligent methodologies and are inspired by the natural immune system to solve real-world problems. In computer science, AIS are a class of computationally intelligent systems inspired by the principles and processes of the vertebrate immune system. The algorithms typically exploit the immune system's characteristics of learning and memory for problem solution. The origins of AIS has its roots in the early theoretical immunology work by Farmer et al. (1986), whereas first known application of algorithm to scheduling was presented by Hart et al. (1998).

The research work addressing AIS application to FJSSP is shown in Table 5.

5.4. Evolutionary algorithms

Algorithms are a subset of evolutionary computation. EA is a generic population-based metaheuristic optimization algorithm that is inspired by natural evolution. EAs consist of several heuristics that are able to solve optimization tasks by imitating some aspects of natural evolution. An EA

Table 5
Applications AIS in FJSSP

Article	Application	Algorithm and shop details	Objective function	Citations
Bagheri et al. (2010)	Research	Artificial immune algorithm (AIA) that uses a combination of strategies is utilized for generating the initial population. Algorithm also employs multiple different mutations for reassigning and resequencing	Makespan	100
Akhshabi et al. (2011b)	Research	Clonal selection algorithm (CSA) to solve FJSSP	Makespan	7
Davarzani et al. (2012)	Research	Multi-objective AIA based on Pareto optimality based on an integrated approach to solve a stochastic FJSSP	Minimum of makespan, workload of most loaded machine, total workload of machines	2
Davoudpour and Azad (2012)	Research	AIS for solving multiobjective. Proposed approach efficiently solves large scale problems	Minimum of makespan, workload of most loaded machine, total workload of machines	–
Sadrzadeh (2013)	Research	AIS for FJSSP with sequence-dependent setup times	Minimum of makespan and mean tardiness	6

uses mechanisms inspired by biological evolution, such as reproduction, mutation, recombination, and selection. Candidate solutions to the optimization problem play the role of individuals in a population, while fitness function determines quality of the solutions. Evolution of the population takes place after repeated application of the above operators. Some of the well-known EA methods are listed below.

1. *Biogeography-based optimization (BBO)* – it is an EA that optimizes a function by stochastically and iteratively improving candidate solutions with regard to a given measure of quality, or fitness function.
2. *Differential evolution (DE)* – it is based on vector differences and is therefore primarily suited for numerical optimization problems.
3. *Evolution strategy (ES)* – it works with vectors of real numbers as representations of solutions, and typically uses self-adaptive mutation rates.
4. *Gene expression programming (GEP)* – GEP explores a genotype–phenotype system, where computer programs of different sizes are encoded in linear chromosomes of a fixed length.
5. *Genetic Algorithms (GA)* – this is most popular type of EA. One seeks the solution of a problem in the form of strings of numbers, by applying operators such as recombination and mutation.

6. *Genetic programming (GP)* – solutions are in the form of computer programs, and their fitness is determined by their ability to solve a computational problem.
7. *Harmony Search (HS)* – population-based stochastic algorithm that mimics the behavior of a music orchestra when aiming at composing the most harmonious melody, as measured by aesthetic standards.
8. *Learning classifier system (LCS)* – it is a machine learning technique that combines evolutionary computing, reinforcement learning, supervised or unsupervised learning, and heuristics to produce adaptive systems.
9. *Memetic Algorithms (MA)* – EAs in which two search techniques are combined, genetic algorithms and some form of local search.
10. *Estimation of distribution algorithm (EDA)* – EDAs are also called probabilistic model-building genetic algorithms. These are stochastic optimization methods that guide the search for the optimum by building and sampling explicit probabilistic models of promising candidate solutions.

The research work addressing EA application to FJSSP is shown in Table 6.

5.5. *Greedy randomized adaptive search procedure (GRASP)*

GRASP is a metaheuristic algorithm commonly applied to combinatorial optimization problems. It was first introduced by Feo and Resende (1989). Each iteration consists of two phases: construction and local search. The construction phase builds a solution, when this solution is not feasible, it is necessary to apply a repair procedure to achieve feasibility. However, when a feasible solution is obtained, its neighborhood is investigated until a local minimum is found during the local search phase (Resende and Ribeiro, 2010).

Rajkumar et al. (2010) with 16 citations consider FJSSP with nonfixed availability constraints where machines are unavailable due to preventive maintenance and proposed GRASP algorithm to minimize makespan, workload of most loaded machine, and total workload of machines. Rajkumar et al. (2011) with 16 citations present a GRASP algorithm to minimize makespan, workload of most loaded machine, and total workload of machines in an FJSSP with limited resource constraints. The main constraint of this scheduling problem is that each operation of a job must follow an appointed process order and each operation must be processed on an appointed machine.

5.6. *Integer/Linear programming*

An integer/linear programming problem is a mathematical optimization or feasibility program in which some or all of the variables are restricted to be integers. In many settings, the term refers to integer linear programming, in which the objective function and the constraints (other than the integer constraints) are linear. The method was first developed by Kantorovich (1940) for use during World War II to plan expenditures and returns in order to reduce costs to the army and increase losses to the enemy. The method was kept secret until 1947 when George B. Dantzig published the

Table 6
Applications of EAs in FJSSP

Article	Application	Algorithm and shop details	Objective function	Citations
Jensen (2003)	Research	GA, rescheduling in a dynamic FJSSP with machine breakdowns	Makespan	166
Kis (2003)	Research	GA	Makespan	55
Kim et al. (2003)	Research	Symbiotic EA that simultaneously solves process planning and scheduling	Makespan	237
Jang et al. (2003)	Research	GA, FJSSP with multilevel job structures where end products are assembled from subassemblies or manufactured components	Total tardiness	4
Zhang and Gen (2005)	Research	Multistage operation-based GA to solve FJSSP	Minimum of makespan, workload of most loaded machine, total workload of machines	236
Chan et al. (2006)	Research	GA-based approach to solve a resource-constrained operations-machines assignment problem and flexible job-shop scheduling problem	Makespan	64
Ho et al. (2007)	Research	LEarnable Genetic Architecture (LEGA), that provides an effective integration between evolution and learning within a random search process	Makespan	131
Pezzella et al. (2008)	Research	GA that integrates different strategies for generating the initial population, selecting the individuals for reproduction, and reproducing new individuals	Makespan	393
Zandieh et al. (2008)	Research	GA	Makespan	1
Saad et al. (2008)	Research	GA with choquet integral for dealing with multiple criteria decision making	Minimum of makespan, workload of most loaded machine, total workload of machines, sum of weighted earliness and weighted tardiness, sum of production cost	29
Li and Huo (2009)	Industry	GA, FJSSP with setup times, consideration of maintenance planning and intermediate inventory restriction	Total setup time on machines and waiting time of jobs	11

Continued

Table 6
Continued

Article	Application	Algorithm and shop details	Objective function	Citations
Lei (2010)	Research	Decomposition-integration GA, FJSSP with fuzzy processing times	Minimization of fuzzy makespan	56
De Giovanni and Pezzella (2010)	Research	GA, FJSSP in distributed manufacturing environment where jobs are processed by a system of several flexible manufacturing units (FMUs)	Makespan for all FMUs	118
Fattahi and Fallahi (2010)	Research	GA, dynamic FJSSP with addition of new jobs and machines	Minimum of efficiency and stability of schedules where (stability = starting time deviation + total deviation penalty)	27
Sun et al. (2010)	Research	GA, FJSSP with partial flexibility and JIT request	Makespan	3
Moradi et al. (2010)	Research	Learnable genetic architecture (LEGA), FJSSP with preventive maintenance	Makespan	13
Defersha and Chen (2010)	Research	Parallel GA, FJSSP with sequence-dependent setup time, attached or detached setup time, machine release dates, and time lag requirements between finish and start times of two successive operations of a job	Makespan	17
Rahmati and Zandieh (2011)	Research	Biogeography-based optimization (BBO) algorithm	Minimum of makespan, workload of most loaded machine, total workload of machines	30
Mati et al. (2011)	Research	GA, FJSSP with blocking constraints whereby buffer capacity between workstations is limited	Makespan	9
Al-Hinai and Elmekkawy (2011bb)	Research	Two-stage GA, FJSSP with random machine breakdowns	Makespan	54
Zhang et al. (2011)	Research	GA with global selection, local selection, and random selection procedures for generating initial solution	Makespan	90
Ida and Oka (2011)	Research	GA	Minimum of maximum workload	–

Continued

Table 6
Continued

Article	Application	Algorithm and shop details	Objective function	Citations
Farughi et al. (2011)	Research	MA, FJSSP with overlapping in operations where start of successor operation of job not necessarily starts after the finish of its predecessor	Makespan	–
Moradi et al. (2011)	Research	Nondominated sort GA (NSGA-II), FJSSP with fixed interval preventive maintenance	Minimum of makespan for the production part and the minimum of the system unavailability for maintenance part	55
Nicoara et al. (2011)	Research	GA (NSGA-II) with dynamic application of genetic operators and population partial re-initialization	Minimizing makespan, number of late operations, and average ratio of idle times in workshop	28
Lei (2012)	Research	Co-evolutionary GA (CGA) with a novel representation and crossover operator, the populations of job sequencing and machine assignment evolve independently and cooperate each other to approximate the best solutions of the problem	Minimum of fuzzy makespan	20
Nagamani et al. (2012)	Research	GA	Makespan	–
Vaghefinezhad and Wong (2012)	Research	GA	Maximum of total profit by determining the amount of production in normal time and overtime	–
Lee et al. (2012)	Research	GA for FJSSP with ‘AND’/‘OR’ precedence constraints	Makespan	63
Rabiee et al. (2012)	Research	Four GAs (NSGA-II, NRGA, MOGA and PAES), statistical analysis is also conducted to analyze the performance of the algorithms in five metrics namely nondominated solution, diversification, mean ideal distance, quality metric and data envelopment analysis	Minimum of makespan and total operating cost	20
Chen et al. (2012)	Industry	Grouping GA (GGA), FJSSP with re-entrant processes. GGA consisting of machine selection and operation scheduling module applied in a real weapon production factory	Minimum of makespan, total tardiness and total machine idle time	25

Continued

Table 6
Continued

Article	Application	Algorithm and shop details	Objective function	Citations
Pandian et al. (2012)	Research	GA (NSGA-II) with jumping of genes between chromosomes, FJSSP with AGVs	Minimum makespan and material flow	–
Yegane et al. (2012)	Research	Memetic algorithm (MA), FJSSP with pre-emption and overlapping in operation	Makespan	–
Wang et al. (2012a)	Research	Bipopulation-based estimation of distribution algorithm (BEDA)	Makespan	43
Agrawal et al. (2012)	Research	Multiobjective GA	Minimum of the makespan and total machining time	3
Gen and Lin (2012)	Research	Multistage operation based GA (moGA), FJSSP with AGVs and setup times	Minimum of makespan, workload of most loaded machine, total workload of machines	7
Xiong et al. (2013)	Research	EA, FJSSP with random machine breakdowns and job release times	Minimum makespan and robustness of schedules	23
Chiang and Lin (2013)	Research	Simple EA to search for the set of Pareto-optimal solutions	Minimum of makespan, workload of most loaded machine, total workload of machines	26
Wang et al. (2013c)	Research	GA, FJSSP with machine disruptions and rescheduling with special chromosome that uses JIT routing heuristics taking into account the current state of the scheduling environment	Makespan	1
Na and Park (2014)	Research	GA, priority rules and local search rules applied to improve the performance of GA	Total tardiness	4
Nie et al. (2013)	Research	Gene expression programming (GEP), dynamic FJSSP with job release dates	Minimum of makespan, mean flow time, and mean tardiness	15
Yuan and Xu (2013c)	Research	Memetic algorithm (MA) based on NSGA-II	Minimum of makespan, workload of most loaded machine, total workload of machines	–
Zhang et al. (2013)	Research	Memetic algorithm (MA), dynamic FJSSP with random job arrivals	Minimum of makespan and mean tardiness	–

Continued

Table 6
Continued

Article	Application	Algorithm and shop details	Objective function	Citations
Rahmati et al. (2013)	Research	Nondominated sorting GA (NSGA-II) and nondominated ranking genetic algorithm (NRGA)	Minimum of makespan, workload of most loaded machine, total workload of machines	14
Gao et al. (2014)	Research	Discrete harmony search (HS)	Minimum of makespan and mean earliness and tardiness	2
Zambrano Rey et al. (2014)	Research	GA, FJSSP with distributed arrival-time, JIT dynamic scheduling	Minimum quadratic relationship between the earliness and tardiness penalties	2

simplex method and John von Neumann developed the theory of duality as a linear optimization solution, and applied it in the field of game theory. In the postwar era, numerous industries found its use in their daily planning. Since then the method has had important application in various fields most notably being operations research, production planning, and scheduling. The significant applications of integer/linear programming are given in Table 7.

5.7. *Neighborhood search (NS)*

Variable neighborhood search is a relatively unexplored approach. VNS is a metaheuristic method for solving a set of combinatorial optimization and global optimization problems. It explores distant neighborhoods of the current incumbent solution, and moves from there to a new one if an improvement was noted. The local search method is applied repeatedly to solutions obtained from the neighborhood to local optima. VNS was first proposed by Mladenović and Hansen (1997). VNS was designed for approximating solutions of discrete and continuous optimization problems, it is aimed for solving linear, integer, mixed integer, and nonlinear program problems, etc. VNS applications in FJSSP are shown in Table 8.

5.8. *Particle swarm optimization (PSO)*

Particle swarm optimization (PSO) is a swarm-based optimization technique developed by Eberhart and Kennedy (1995) and Kennedy and Eberhart (1995). The algorithm is inspired by the flocking and schooling patterns of birds and fish. PSO algorithm is an adaptive algorithm based on a social-psychological metaphor; a population of individuals adapts by returning stochastically toward previously successful regions. PSO is an approach to problems whose solutions can be represented as a point in an n-dimensional solution space. A number of "particles" are randomly set into motion

Table 7
Applications of integer/linear programming in FJSSP

Article	Application	Algorithm and shop details	Objective function	Citations
Thomalla (2001)	Research	Discrete-time integer programming (IP) based on the Lagrangian relaxation. FJSSP with just-in-time environment.	Minimum of sum of weighted quadratic tardiness	62
Gomes et al. (2005)	Industry	Integer linear programming. FJSSP with discrete parts manufacturing industries that operate on a make-to-order basis, parallel homogeneous machines, limited intermediate buffers and re-entrant machines	Costs derived from failing to meet the 'just in time' due dates, in-process inventory costs, and costs of orders not fully completed at the end of the scheduling horizon	39
Özgüven et al. (2010)	Research	MILP. FJSSP with routing and process plan flexibility	Makespan	63
Gomes et al. (2013)	Research	MILP. FJSSP in make-to-order industries, re-entrant processes and final assembly stage considered simultaneously	Minimum of weighted sum of order earliness, order tardiness and in-process inventory	4
Mousakhani (2013)	Research	MILP. FJSSP with sequence-dependent setup times	Total tardiness	5
Birgin et al. (2013)	Industry	MILP. An extended FJSSP is presented where precedence between operations of a job to be are given by an arbitrary directed acyclic graph rather than a linear order	Makespan	3
Roshanaei et al. (2013)	Research	MILP	Makespan	6
Hansmann et al. (2013)	Industry	MILP with B&B procedure. FJSSP with machine blockages or machines with restricted accessibility, that is, a busy machine blocks access to all succeeding machines	Makespan	–
Torabi et al. (2005)	Research	MINLP procedure for simultaneous determination of machine allocation, sequencing, economic lot-sizing, and scheduling decisions	Minimum the sum of setup and inventory holding costs per time unit without backlogging	41
Özgüven et al. (2012)	Research	Mixed integer goal programming. FJSSP with separable/nonseparable sequence-dependent setup times	Minimum makespan and balancing the workloads of the machines	10

Table 8
Applications of VNS in FJSSP

Article	Application	Algorithm and shop details	Objective function	Citations
Yazdani et al. (2010)	Research	Parallel variable neighborhood search (PVNS) to increases the diversification and exploration in search space	Makespan	123
Amiri et al. (2010)	Research	VNS	Makespan	35
Lei and Guo (2011)	Research	Swarm-based NS, FJSSP with fuzzy processing conditions	Fuzzy makespan	7
Bagheri and Zandieh (2011)	Research	VNS, FJSSP with sequence-dependent setup times	Minimum of makespan and mean tardiness	15
Zheng et al. (2012)	Research	Multiobjective swarm-based neighborhood search (MOSNS), FJSSP with fuzzy processing times	Minimum of fuzzy makespan and maximum machine workload	6
Lei and Guo (2014)	Research	VNS with two neighborhood-search procedures, Dual-resource (machines & workers) constrained FJSSP	Makespan	1

through this space. At each iteration, they observe the “fitness” of themselves and their neighbors and “emulate” successful neighbors (those whose current position represents a better solution to the problem than theirs) by moving toward them. Various schemes for grouping particles into competing, semi-independent “flocks” can be used, or all the particles can belong to a single global flock. This extremely simple approach has been effective across a variety of problem domains. Applications of PSO in FJSSP are given in Table 9.

5.9. *Simulated annealing (SA)*

SA is a random-search technique that exploits an analogy to the process in which a metal cools and freezes into a minimum energy crystalline structure and search for a minimum in a more general system; it forms the basis of an optimization technique for combinatorial and other problems.

SA was developed in 1983 by Kirkpatrick and Vecchi (1983) to deal with highly nonlinear problems. SA approaches the global maximization problem similar to using a bouncing ball that can bounce over mountains from valley to valley. It begins at a high "temperature," which enables the ball to make very high bounces, it bounces over any mountain to access any valley, given enough bounces. As the temperature drops the ball cannot bounce so high, and it gets trapped in relatively small ranges of valleys. A generating distribution generates possible valleys or states to be explored. An acceptance distribution is also defined, which depends on the difference between the function value of the present generated valley to be explored and the last saved lowest

Table 9
Applications of PSO in FJSSP

Article	Application	Algorithm and shop details	Objective function	Citations
Boukef et al. (2008)	Research	PSO	Makespan	5
Pongchairerks and Kachitvichyanukul (2009)	Research	PSO with multiple social learning topologies in its evolutionary process	Makespan	14
Liu et al. (2009)	Research	Multiswarm PSO	Minimum makespan of total flow time	28
Grobler et al. (2010)	Industry	PSO, FJSSP with sequence-dependent setup times, auxiliary resources and machine down time	Minimum of makespan, earliness/tardiness, and queue times	5
Mekni et al. (2011)	Research	Parameter-free PSO that does not require any parameter tuning (swarm size, sociometry, etc.)	Makespan	–
Akhshabi et al. (2011a)	Research	PSO	Makespan	2
Mekni et al. (2012)	Research	Parameter-free PSO that does not require any parameter tuning	Minimum of makespan, workload of most loaded machine, total workload of machines	–
Sadrzadeh (2013)	Research	PSO, FJSSP with sequence-dependent setup times	Minimum of makespan and mean tardiness	6

valley. The acceptance distribution decides probabilistically whether to stay in a new lower valley or to bounce out of it. All the generating and acceptance distributions depend on the state of temperature.

Loukil et al. (2007) with 73 citations consider a real-life case study and propose an SA algorithm to minimize makespan, the mean completion time, maximal tardiness, and mean tardiness. Authors also consider various constraints such as batch production—production of several subproducts followed by the assembly of the final product, and possible overlaps for the processing periods of two successive operations of a same job. Fattahi et al. (2009) having 30 citations propose an SA algorithm to minimize makespan in an FJSSP with overlapping in operations. The authors argue that it can be easily adapted for other single objective optimization problems such as minimization of total weighted tardiness. Yazdani et al. (2009) also propose an SA algorithm to minimize makespan in FJSSP. In order to search the solution space, the authors use neighborhood structures of assignment of jobs to machines and sequencing of assigned jobs on a particular machine to generate neighboring solutions. Khalife et al. (2010) having one citation consider minimizing makespan, workload of most loaded machine, total workload of machines for an FJSSP with overlapping in operations, and propose an SA algorithm to solve the problem.

5.10. Tabu search (TS)

TS is a metaheuristic method originally proposed by Glover (1986). It guides a local heuristic search procedure to explore the solution space beyond local optimality. TS is based on the premise that problem solving, to qualify as intelligent, must incorporate adaptive memory and responsive exploration. The adaptive memory feature of TS allows the implementation of procedures that are capable of searching the solution space economically and effectively. As local choices are guided by information collected during the search, TS contrasts with memory-less design that heavily rely on semi-random processes that implement a form of sampling. The emphasis on responsive exploration in TS, whether in a deterministic or probabilistic implementation, derives from the supposition that a bad strategic choice can often yield more information than a good random choice. Over a wide range of problem settings, strategic use of memory can make dramatic differences in the ability to solve problems. Application of TS in FJSSP is given in Table 10.

5.11. Mathematical programming

A mathematical model is an abstract model that uses mathematical language to describe the behavior of a system. Mathematical models are used particularly in the natural sciences and engineering disciplines such as physics, biology, and electrical engineering, but also in the social sciences such as economics, sociology, and political science; physicists, engineers, computer scientists, and economists use mathematical models most extensively. Eykhoff (1974) defined a mathematical model as "a representation of the essential aspects of an existing system (or a system to be constructed) presenting its knowledge in usable form." Mathematical models can take many forms, including but not limited to dynamical systems, statistical models, differential equations, or game theoretic models.

Elazeem et al. (2011) introduced a mathematical model of the primal problem of FJSSP to minimize the makespan and its dual problem (Abdou's problem). The authors show that the optimal value of Abdou's problem is a lower bound for the objective value of the primal problem. Sun et al. (2014) having one citation propose a new model for FJSSP with machine breakdown based on noncooperative game theory. The authors also propose an algorithm to find the Nash Equilibrium or near-Nash Equilibrium solutions. Robustness and stability are the two measures used by the authors to evaluate the quality of rescheduling. Experiments show that applying game theory can find solution with better performance for both robustness and stability as compared to other rescheduling strategies. Yulianty and Ma'ruf (2013) developed mathematical models for FJSSP with controllable processing time and expected downtime by using predictive approach with minimization of rescheduling cost and tardiness as the objective functions. The authors developed mathematical models to build an initial solution that determines job assignment and processing times of the jobs. The initial solution is later used for rescheduling jobs by considering expected downtime for each machine and downtime probability for each operation. Demir and Kürşat İşleyen (2013) having 25 citations consider various mathematical formulations of FJSSP compiled from literature and propose a time-indexed model to minimize makespan. The models are investigated in terms of binary variables that rely on using sequencing operations on machines named sequence-position,

Table 10
Applications of TS in FJSSP

Article	Application	Algorithm and shop details	Objective function	Citations
Brandimarte (1993)	Research	Hierarchical approach based on TS by decomposing the problem into assignment and scheduling subproblems	Minimum of makespan and total weighted tardiness	434
Hurink et al. (1994)	Research	TS	Makespan	240
Mastrolilli and Gambardella (2000)	Research	TS by reducing the set of possible neighbors to a subset that always contains neighbor with the lowest makespan	Makespan	370
Kis (2003)	Research	TS	Makespan	55
Scrich et al. (2004)	Research	Hierarchical and multistart TS	Total tardiness	73
Saidi-Mehrabad and Fattahi (2007)	Research	TS with an adjacent pairwise interchange method to generate the neighborhoods, FJSSP with sequence-dependent setup times	Makespan	18
Ennigrou and Ghédira (2008)	Research	TS-based multiagent systems composed of three agent classes: job agents, resource agents, and an interface agent	Makespan	18
Bożejko et al. (2010)	Research	Parallel TS with two major modules: machine selection module executed sequentially, and operation scheduling module executed in parallel	Makespan	6
Vilcot and Billaut (2011)	Industry	TS	Minimum of makespan, maximum lateness and total tardiness	17
Bożejko et al. (2012)	Research	Parallel TS implemented on multi-GPU	Makespan	–
Lee et al. (2012)	Research	TS	Makespan	63
Jia and Hu (2014)	Research	Path-relinking TS with back-jump tracking	Minimum of makespan, workload of most loaded machine, total workload of machines	3

precedence, and time-indexed variables and compare the computational efficiency of models. Mixed integer linear programming (MILP) is used to solve these mathematical formulations.

5.12. Deterministic heuristics

Various authors have proposed deterministic heuristics for solving FJSSP. Given a particular input, deterministic heuristics always produce same output, with the underlying machine always passing through the same sequence of states. While nondeterministic heuristics explicitly involve a random variable. Different individuals using the same algorithm will get different answers. Metaheuristics such as GA, TS, PSO, ACO, SA, and so on, are all nondeterministic methods. Deterministic heuristics used by researchers are generally based on various dispatching rules. The summary of application of heuristics in FJSSP is given in Table 11.

5.13. Hybrid techniques

In the recent years hybrid techniques have become more popular among researchers as compared to pure heuristics or metaheuristics. These techniques combine one or more heuristic or metaheuristic to take advantage of their strengths. Applications of various hybrid techniques employed by researchers in FJSSP are given in Table 12.

5.14. Miscellaneous techniques

A single instance/application of a technique has been classified as a miscellaneous technique's category. Applications of various miscellaneous techniques in FJSSP are given in Table 13.

6. Analysis and discussion

Flexible JSS is considered to be an important area of research and thus falls among the most published class of problems in a manufacturing system. An optimal schedule is difficult to develop due to NP-hard nature of FJSSP. Due to the practical nature of this problem, a large number of researchers have addressed it and proposed various efficient techniques/methods. A total of 404 research publications were found having addressed the problem. In this survey, we have focused on 191 journal publications published from 1990 to February 2014. A total of 197 different solution techniques/methods were used in these papers.

The techniques/methods proposed in 191 journal papers have been categorized in 14 major categories namely: ACO, ABC, AIS, EAs, GRASP, Heuristics, Hybrid Techniques, Integer/Linear Programming, Mathematical Modeling, Miscellaneous Techniques, NS, PSO, SA, and TS.

This survey revealed the following facts:

1. Publications addressing FJSSP has grown significantly from 2010 onwards that signifies the importance of the problem under review.
2. Country-wise analysis was also performed to ascertain the country of research publication origination. The publications are attributed to a country based on the address of its first author. Country-wise distribution of papers is tabulated in Table 14. The results reveal that China leads the table with a total of 59 publications with Iran following at second and France at third positions with 44 and nine papers, respectively. A total of 213 research papers addressing FJSSP are also presented in various level of conferences. Country-wise distribution of work presented

Table 11
Application of deterministic heuristics in FJSSP

Article	Application	Algorithm and shop details	Objective function	Citations
Brucker and Schlie (1990)	Research	Polynomial algorithm, 2 Job FJSSP	Makespan	289
Golenko-Ginzburg and Laslo (2004)	Research	Dispatching rules based on a cyclic coordinate descent method, and a simulation model comprising a modified decision-making rule for cost objectives	Minimum of average scheduling expanses within the time period	–
Wu and Weng (2005)	Research	Agent-based heuristic	Minimum of earliness and tardiness	47
Alvarez-Valdes et al. (2005)	Industry	Heuristic algorithm based on priority rules, FJSSP with no-wait constraints	Minimum the total cost associated to the finishing times of the jobs corresponding to final products	53
Chen et al. (2007)	Industry	Heuristic based on priority rules, FJSSP with re-entrant processes where certain machines are visited more than once	Minimum of maximum lateness and average tardiness	35
Fahmy et al. (2007)	Research	Heuristic with rank matrices (Latin rectangles) to insert new jobs in schedules, FJSSP with reactive rescheduling	Efficiency of the revised schedules in terms of the mean flow time, resulting system nervousness, and the required solution time	2
Shi-Jin et al. (2008)	Research	Heuristic based on filtered beam search algorithm (Ow and Morton, 1988)	Minimum of makespan, workload of most loaded machine, total workload of machines	21
Chen and Frank Chen (2008)	Research	Heuristic based on priority rules, FJSSP under demand changes	Maximum utilization of all machine	5
Taghavi-Fard and Saidy (2009)	Research	Heuristic implementing Aker's graphical algorithm (Akers and Friedman, 1955), FJSSP with machine nonavailability constraints	Makespan	–
Baykasoğlu and Özbakır (2010)	Research	Effect of dispatching rules on the scheduling performance through grammars	Minimum of mean tardiness	19

Continued

Table 11
Continued

Article	Application	Algorithm and shop details	Objective function	Citations
Wang and Yu (2010)	Research	Heuristic based on filtered beam search algorithm (Ow and Morton, 1988), FJSSP with preventive maintenance	Minimum of makespan, workload of most loaded machine, total workload of machines	41
Ham et al. (2011)	Research	Real-time scheduling heuristic based on binary integer programming, FJSSP with real-time scheduling	Makespan	8
Liu and Zhang (2012)	Research	Online scheduling based on dispatching rules	Makespan	–
Lee et al. (2012)	Research	Heuristic	Minimum of makespan and mean flow time	63
Ziaee (2013)	Research	Heuristic based on a constructive procedure	Makespan	2
Calleja and Pastor (2013)	Industry	Heuristic based on priority rules, FJSSP with transfer batches	Minimum of average tardiness	2
Doh et al. (2013)	Research	Heuristic with priority rules	Minimum of makespan, total flow time, mean tardiness, the number of tardy jobs, and the max tardiness	8
Pérez and Raupp (2014)	Research	Newton's method (Fliege et al., 2009) based hierarchical heuristic algorithm	Minimum of makespan, workload of most loaded machine, total workload of machines	3
Sadaghiani et al. (2014)	Research	Pareto archive floating search procedure	Minimum of makespan, workload of most loaded machine, total workload of machines	–

and published in conferences is tabulated in Table 15. Of 404 papers collected during the study, a major chunk of papers almost 54% papers were from only two countries, that is, China (41.58%) and Iran (12.38%).

3. Papers on FJSSP have appeared in 84 different journals. Of a total of 191 research papers, 66% of the papers appeared in 21 journals with a cumulative impact factor of 193.79 as mentioned in

Table 12
Application of hybrid techniques in FJSSP

Article	Application	Algorithm and shop details	Objective function	Citations
Dauzère-Pérès and Paulli (1997)	Research	TS with disjunctive graph model	Makespan	232
Mesghouni et al. (1999)	Research	GA + constraint logic programming	Minimum of Makespan, SD of workload of the resource, mean completion time of the manufacturing orders and SD of the completion time of the manufacturing orders	27
Baykasoğlu (2002)	Research	SA based on linguistic and Giffler and Thompson (Giffler and Thompson, 1960) priority rule	Makespan	45
Kacem et al. (2002a)	Research	Localization approach + controlled GA	Minimum of makespan, workload of most loaded machine, total workload of machines	116
Kacem et al. (2002b)	Research	Pareto-optimality based fuzzy EA	Minimum of makespan, workload of most loaded machine, total workload of machines	351
Tanev et al. (2004)	Industry	GA + priority dispatching rules	Minimum ratio of tardy jobs, variance of the flow time, amount of mold changes and maximum efficiency of machines	59
Baykasoğlu et al. (2004)	Research	TS based on grammars and Giffler and Thompson priority rule	Min of makespan and mean tardiness	55
Xia and Wu (2005)	Research	PSO + SA	Minimum of makespan, workload of most loaded machine, total workload of machines	478
Gao et al. (2006)	Research	GA + local search (LS). FJSSP with maintenance constraints	Minimum of makespan, workload of most loaded machine, total workload of machines	79
Butt and Hou-Fang (2006)	Research	GA + scheduling rules	Makespan	–
Imanipour and Zegordi (2006)	Research	TS + backward procedure heuristic	Minimum of total weighted earliness/tardiness	7

Continued

Table 12
Continued

Article	Application	Algorithm and shop details	Objective function	Citations
Liouane et al. (2007)	Research	ACO + TS	Makespan	–
Zribi et al. (2007)	Research	GA + local search (LS)	Makespan	26
Gao et al. (2007)	Research	GA + local search (LS) procedure based on shifting bottleneck	Minimum of makespan, workload of most loaded machine, total workload of machines	123
Fattahi et al. (2007)	Research	TS + SA	Makespan	133
Ho and Tay (2008)	Research	GA + guided local search	Minimum of makespan, workload of most loaded machine, total workload of machines	48
Gao et al. (2008)	Research	GA + variable neighborhood descent	Minimum of makespan, workload of most loaded machine, total workload of machines	270
Tay and Ho (2008)	Research	Genetic programming + dispatching rules	Minimum of makespan, mean tardiness, and mean flow time	190
Li et al. (2008)	Research	PSO + TS	Makespan	8
Girish and Jawahar (2009)	Research	GA + ACO	Makespan	22
Gholami and Zandieh (2009)	Research	GA + simulation. Dynamic FJSSP with stochastic breakdowns	Makespan Minimum of mean tardiness	56
Zhang et al. (2009)	Research	PSO + TS	Minimum of makespan, workload of most loaded machine, total workload of machines	197
Xing et al. (2010)	Research	ACO + knowledge model	Makespan	142
Motaghedi-Larijani et al. (2010)	Research	GA + hill climbing	Minimum of makespan, workload of most loaded machine, total workload of machines	13
Li et al. (2010c)	Research	GA + VNS	Minimum of makespan, workload of most loaded machine, total workload of machines	5

Continued

Table 12
Continued

Article	Application	Algorithm and shop details	Objective function	Citations
Wang et al. (2010)	Research	GA based on immune and entropy principle	Minimum of makespan, workload of most loaded machine, total workload of machines	61
Lan et al. (2010)	Research	GA with immune mechanism and SA strategy	Minimum of makespan and production costs	–
Frutos et al. (2010)	Research	Memetic algorithm based on the NSGAII acting on two chromosomes with SA for local search (LS)	Minimum of makespan and production costs	25
Rajabinasab and Mansour (2010)	Research	Pheromone-based multiagent scheduling system. FJSSP with stochastic job arrivals, uncertain processing time, and unexpected machine breakdowns	Various performance measures such as mean flow time, maximum flow time etc.	45
Li et al. (2010b)	Research	PSO + TS	Makespan	10
Mahdavi et al. (2010)	Research	Simulation-based DSS	Makespan	40
Li et al. (2010a)	Research	TS + VNS	Minimum of makespan, workload of most loaded machine, total workload of machines	81
Li et al. (2011c)	Research	TS + public critical block neighborhood structure	Makespan	68
Xing et al. (2011)	Research	GA + ACO	Makespan	14
Al-Hinai and Elmekkawy (2011a)	Research	GA + local search (LS)	Makespan	22
Jiang et al. (2011)	Research	GA + SA	Minimum of makespan and total workload of machines	5
Gutiérrez and García-Magariño (2011)	Research	GA with heuristics	Makespan	23
Li et al. (2011d)	Research	Pareto-based ABC algorithm	Minimum of makespan, workload of most loaded machine, total workload of machines	19
Li et al. (2011b)	Research	Pareto-based discrete ABC	Minimum of makespan, workload of most loaded machine, total workload of machines	71

Continued

Table 12
Continued

Article	Application	Algorithm and shop details	Objective function	Citations
Li et al. (2011a)	Research	Pareto-based local search embedding a VNS-based self-adaptive strategy	Minimum of makespan, workload of most loaded machine, total workload of machines	12
Moslehi and Mahnam (2011)	Research	PSO + local search	Minimum of makespan, workload of most loaded machine, total workload of machines	127
Tavakkoli-Moghaddam et al. (2012)	Research	Duplicate GA where initial population is generated randomly in the GA to find a semi-active solution which then evolves by using TS in a certain neighborhood structure as an active solution. Secondary population of the DGA is composed of all active solutions, finally GA is used for the convergence the secondary population	Minimum of makespan and total idleness	–
Xiong et al. (2012)	Research	GA + local search (LS) based on critical path theory	Minimum of makespan, workload of most loaded machine, total workload of machines	4
Dalfard and Mohammadi (2012)	Research	GA + SA. FJSSP with parallel machines and maintenance constraints	Minimum of makespan, average completion time, and tardiness with penalty	13
Zhang et al. (2012)	Research	GA + TS. FJSSP with transportation constraints and bounded processing times	Makespan	25
Barzegar et al. (2012a)	Research	GS algorithm + color petri nets	Makespan	5
Karimi et al. (2012)	Research	Knowledge-based VNS	Makespan	5
Wang et al. (2012b)	Research	Pareto-based ABC + local search based on critical path	Minimum of makespan, workload of most loaded machine, total workload of machines	20
Li et al. (2012)	Research	Shuffled frog-leaping algorithm + local search	Minimum of makespan, workload of most loaded machine, total workload of machines	27

Continued

Table 12
Continued

Article	Application	Algorithm and shop details	Objective function	Citations
Li and Pan (2012)	Research	TS + discrete chemical reaction optimization. FJSSP with maintenance activity	Minimum of makespan, workload of most loaded machine, total workload of machines	15
Wang et al. (2013b)	Research	ABC + VNS. FJSSP with fuzzy processing times	Minimum of fuzzy makespan	14
Roshanaei et al. (2013)	Research	AIS + SA	Makespan	6
Yuan and Xu (2013a)	Research	DE algorithm + local search	Makespan	9
Xu et al. (2013)	Research	Discrete DE algorithm + local search (LS) strategy based on critical path. FJSSP with lot splitting with capacity constraints	Minimum of total production costs, setup costs and tardiness penalty costs	1
Shao et al. (2013)	Research	Discrete PSO + SA	Minimum of makespan, workload of most loaded machine, total workload of machines	15
Nagamani et al. (2013)	Research	EA + hill climbing algorithm	Minimum of makespan, workload of most loaded machine, total workload of machines	–
Zhou and Zeng (2013)	Research	GA + SA	Minimum of makespan and sum of SD of processing workload for all working centers	–
Jalilvand-Nejad and Fattahi (2013)	Research	GA + SA	Minimum the total cost including delay costs, setup costs and holding costs	5
Shahsavari-Pour and Ghasemisha-bankareh (2013)	Research	GA + SA	Minimum of makespan, workload of most loaded machine, total workload of machines	5
Geyik and Dosdoğru (2013)	Research	GA + simulation. Dynamic FJSSP	Total of average flow times	1
Araghi et al. (2013)	Research	GA + VNS with affinity function. FJSSP with sequence-dependent setup times	Makespan	2
Barzegar and Motameni (2013)	Research	Gravitational search (GS) algorithm + PSO	Makespan	–

Continued

Table 12
Continued

Article	Application	Algorithm and shop details	Objective function	Citations
Yuan and Xu (2013b)	Research	Harmony search (HS) + large neighborhood search (LNS) to improve solutions found by HS	Makespan	7
Yuan et al. (2013)	Research	HHS + local search	Makespan	17
Farughi et al. (2013)	Research	Memetic algorithm (MA) + critical path method. FJSSP with overlapping operations	Makespan	1
Wang et al. (2013a)	Research	Pareto-based estimation of distribution algorithm (EDA) + local search strategy based on critical path	Minimum of makespan, workload of most loaded machine, total workload of machines	15
He et al. (2013)	Research	Pareto-optimal based immune clone algorithm with Nash equilibrium. FJSSP with machine breakdown	Minimum of makespan, stability based on end time of each operation and stability based on machine allocation for each operation	–
Li et al. (2014)	Research	ABC + TS. FJSSP with maintenance activities	Minimum of makespan, workload of most loaded machine, total workload of machines	9

Table 16 while remaining 34% papers appearing in 64 journals have a cumulative impact factor of 38.27.

4. Most of the researchers focused on the algorithm development as compared to application in real-world industrial problems. Of 191 journal papers, 179 papers (93.72%) were pure research oriented while only 12 papers (6.28%) addressed the real-world industrial applications.
5. The research articles addressed both single-objective and multiobjective performance measures to evaluate the schedule. A total of 53.09% of the papers addressed single objective while 46.91% were multiobjective performance measures.
6. Minimization of makespan or total completion time had been the most widely used performance measure. Makespan was used in a total of 166 papers, that is, 84.26%. Of these 166 papers, 88 papers (44.67%) of all papers addressed makespan as the single performance measure while 78 papers used makespan in combination with other performance measures. Among multiobjective performance measures minimization of makespan, workload of most loaded machine, and total workload of machines have been the most widely used performance measure with 23.86% of the papers using this performance measure.

Table 13
Application of miscellaneous techniques in FJSSP

Article	Application	Algorithm and shop details	Objective function	Citations
Jansen et al. (2005)	Research	Approximation Algorithm. Job release & delivery times, pre-emption	Makespan	44
Xing et al. (2009a)	Research	Efficient search method	Minimum of makespan, workload of most loaded machine, total workload of machines	62
Xing et al. (2009b)	Research	Simulation	Minimum of makespan, workload of most loaded machine, total workload of machines	86
Hmida et al. (2010)	Research	Climbing depth-bound discrepancy search (CDDS) approach based on ordering heuristics, involves two types of discrepancies, operation selection and resource allocation, and uses the block notion to build neighborhood structures that define relevant variables on which discrepancies are applied	Makespan	39
Barzegar et al. (2012b)	Research	Gravitational Search (GS)	Makespan	2
Sharma (2013)	Research	Attribute-oriented data mining technique	Minimum of makespan, workload of most loaded machine, total workload of machines	–
He and Sun (2013)	Research	Idle time insertion and route changing strategy combined with right-shift policy. FJSSP with machine breakdown, route changing, and right-shift strategies	Makespan	12

7. None of the research claims their technique/method is superior to others in the domain of FJSSP. Almost 80% of the citations, that is, 6809 of total of 8545 were attributable to only three techniques namely: hybrid, EAs, and TS.
8. Hybrid techniques/methods have been the most popular methods with almost 35.03% of the publications relying on hybrid techniques. Hybrid methods have been used to take advantage

Table 14
Country-wise distribution of research papers in journals

Country	Total
China	59
Iran	44
France	9
India	8
Turkey, Tunisia	7
Canada, South Korea	5 each
Brazil, Germany, Italy, Singapore, Taiwan	04 each
Japan, Spain, USA	03 each
Poland, Portugal	02 each
Argentina, Denmark, Egypt, Hong Kong, Hungary, Indonesia, Israel, Malaysia, Pakistan, Romania, Saudi Arabia, South Africa, Switzerland, Thailand	01 each

Table 15
Country-wise distribution of research papers other than journals

Country	Total
China	109
France	17
Poland	9
USA	8
Japan, Singapore	7 each
Iran, Turkey	6 each
India, Malaysia, Taiwan, Thailand, Tunisia	4 each
Belgium, Canada, Germany	3 each
Portugal, Sweden	2 each
Brazil, Denmark, Egypt, Holland, Indonesia, Italy, Oman, Pakistan, Saudi Arabia, South Africa, Spain	1 each

of the strengths of each of the methods to find better solutions. A total of 3572 citations for 69 papers have been noted addressing hybrid techniques.

9. Second-most popular technique in terms of total number of papers and citations is EAs. Various EA techniques were used in 23.86% of publications. A total of 1940 citations using EAs toward problem resolution have been noted.
10. Among all techniques used by various researchers whether hybrid or pure, GAs have been the most popular technique, used by 34% of the publications. A total of 2660 citations have been recorded for the publications that have used GAs as a standalone or combination technique. Second-most popular technique is TS with total of 2150 citations.
11. Most of the research papers have addressed simple FJSSP, while only 70 papers (35.53%) considered different scenarios such as setup and transportation times, maintenance, machine breakdown, job/machine ready times, fuzzy/uncertain processing times, overlapping operations, and re-entrant flexible job shop. In these real-like situations GA has been the most

Table 16
Paper distribution in different journals

Journal	Number of papers	Impact factor
International Journal of Production Research	28	1.323
International Journal of Advanced Manufacturing Technology	17	1.779
Journal of Intelligent Manufacturing	10	1.142
Computers & Industrial Engineering	9	1.690
International Journal of Production Economics	8	2.081 (2012)[a]
Computers & Operations Research	7	1.718
Applied Soft Computing	6	2.679
Applied Mathematical Modeling	5	2.158
European Journal of Operational Research	5	1.843
Annals of Operations Research	4	1.103
Expert Systems with Applications	4	1.965
IEEE Transactions on Systems, Man, and Cybernetics, Part C	3	1.526
Journal of Applied Sciences	3	–
Journal of Information and Computational Science	3	–
International Journal of Computers Communications & Control	2	0.694
Journal of Manufacturing Systems	2	1.847
Knowledge-Based Systems	2	3.058
Mathematical Problems in Engineering	2	1.082
Mathematics and Computers in Simulation	2	0.856
Production Planning & Control	2	0.991

[a]Title suppressed in 2013 JCR (http://admin-apps.webofknowledge.com/JCR/static_html/notices/notices.htm).

popular technique used by 24 researchers with total of 749 citations. Among these 24 papers, seven papers used GA in combination with other techniques.

7. Conclusions

The study presented here considered the review of solution techniques/methods published in the literature to solve FJSSPs. The paper presents a critical and comprehensive overview of the research trends in this area.

FJSSPs are an extension of typical JSS problems and are considered difficult to solve due to their NP-hard nature. Researchers and practitioners have tried to develop efficient solution techniques/methods during the last 25 years. With the advancement in computational power, the techniques/methods to solve FJSSP have become more and more efficient and powerful. Metaheuristics have been used more widely as compared to other methods. The most popular techniques have been hybrid methods as these techniques take advantage of the strengths of each of the methods to find better solutions. However, among all techniques, genetic algorithms have been the most widely used in this domain.

In the study, a range of methods have been surveyed. None of the methods has been adjudged the best by any researchers. Most of the work is focused on testing the developed algorithm on benchmark or generated problems. Relatively less work has been reported on practical problem solutions as compared to pure research.

References

Agrawal, R., Pattanaik, L.N., Kumar, S., 2012. Scheduling of a flexible job-shop using a multi-objective genetic algorithm. *Journal of Advances in Management Research* 9, 178–188.

Akers, S.B., Friedman, J., 1955. A non-numerical approach to production scheduling problems. *Operations Research* 3, 429–442.

Akhshabi, M., Akhshabi, M., Khalatbari, J., 2011a. A particle swarm optimization algorithm for solving flexible job-shop scheduling problem. *Journal of Basic and Applied Scientific Research* 1, 3240–3244.

Akhshabi, M., Akhshabi, M., Khalatbari, J., 2011b. Solving flexible job-shop scheduling problem using clonal selection algorithm. *Indian Journal of Science and Technology* 4, 1248–1251.

Al-Hinai, N., Elmekkawy, T.Y., 2011a. An efficient hybridized genetic algorithm architecture for the flexible job shop scheduling problem. *Flexible Services and Manufacturing Journal* 23, 64–85.

Al-Hinai, N., Elmekkawy, T.Y., 2011b. Robust and stable flexible job shop scheduling with random machine breakdowns using a hybrid genetic algorithm. *International Journal of Production Economics* 132, 279–291.

Alvarez-Valdes, R., Fuertes, A., Tamarit, J.M., Giménez, G., Ramos, R., 2005. A heuristic to schedule flexible job-shop in a glass factory. *European Journal of Operational Research* 165, 525–534.

Amiri, M., Zandieh, M., Yazdani, M., Bagheri, A., 2010. A variable neighbourhood search algorithm for the flexible job-shop scheduling problem. *International Journal of Production Research* 48, 5671–5689.

Araghi, M.E.T., Jolai, F., Rabiee, M., 2013. Incorporating learning effect and deterioration for solving a SDST flexible job-shop scheduling problem with a hybrid meta-heuristic approach. *International Journal of Computer Integrated Manufacturing* 27, 733–746.

Bagheri, A., Zandieh, M., 2011. Bi-criteria flexible job-shop scheduling with sequence-dependent setup times – variable neighborhood search approach. *Journal of Manufacturing Systems* 30, 8–15.

Bagheri, A., Zandieh, M., Mahdavi, I., Yazdani, M., 2010. An artificial immune algorithm for the flexible job-shop scheduling problem. *Future Generation Computer Systems* 26, 533–541.

Barzegar, B., Motameni, H., 2013. Solving flexible job-shop scheduling problem using hybrid algorithm based on gravitational search algorithm and particle swarm optimization. *Journal of Advances in Computer Research Quarterly* 4, 69–81.

Barzegar, B., Motameni, H., Bozorgi, H., 2012a. Solving flexible job-shop scheduling problem using gravitational search algorithm and colored petri net. *Journal of Applied Mathematics* 2012, 1–20.

Barzegar, B., Motameni, H., Zarinpour, M., Gholami, F., 2012b. Scheduling analysis of flexible job shop system by improved gravitational search algorithm. *African Journal of Business Management* 6, 7005–7015.

Baykasoğlu, A., 2002. Linguistic-based meta-heuristic optimization model for flexible job shop scheduling. *International Journal of Production Research* 40, 4523–4543.

Baykasoğlu, A., Özbakır, L., 2010. Analyzing the effect of dispatching rules on the scheduling performance through grammar based flexible scheduling system. *International Journal of Production Economics* 124, 369–381.

Baykasoğlu, A., Özbakır, L., Sönmez, A.İ., 2004. Using multiple objective tabu search and grammars to model and solve multi-objective flexible job shop scheduling problems. *Journal of Intelligent Manufacturing* 15, 777–785.

Birgin, E.G., Feofiloff, P., Fernandes, C.G., Melo, E.L., Oshiro, M.T.I., Ronconi, D.P., 2013. A MILP model for an extended version of the flexible job shop problem. *Optimization Letters* 8, 1417–1431.

Boukef, H., Benrejeb, M., Borne, P., 2008. Flexible job-shop scheduling problems resolution inspired from particle swarm optimization. *Studies in Informatics and Control* 17, 33–38.

Bożejko, W., Uchroński, M., Wodecki, M., 2010. Parallel hybrid metaheuristics for the flexible job shop problem. *Computers & Industrial Engineering* 59, 323–333.

Bożejko, W., Uchroński, M., Wodecki, M., 2012. Flexible job shop problem – parallel tabu search algorithm for multi-GPU. *Archives of Control Sciences* 22, 389–397.

Brandimarte, P., 1993. Routing and scheduling in a flexible job shop by tabu search. *Annals of Operations Research* 41, 157–183.

Brucker, P., Schlie, R., 1990. Job-shop scheduling with multi-purpose machines. *Computing* 45, 369–375.

Butt, S.I., Hou-Fang, S., 2006. Application of genetic algorithms and rules in scheduling of flexible job shops. *Journal of Applied Sciences* 6, 1586–1590.

Calleja, G., Pastor, R., 2013. A dispatching algorithm for flexible job-shop scheduling with transfer batches: an industrial application. *Production Planning & Control* 25, 93–109.

Chan, F.T.S., Wong, T.C., Chan, L.Y., 2006. Flexible job-shop scheduling problem under resource constraints. *International Journal of Production Research* 44, 2071–2089.

Chen, J.C., Chen, K.H., Wu, J.J., Chen, C.W., 2007. A study of the flexible job shop scheduling problem with parallel machines and reentrant process. *International Journal of Advanced Manufacturing Technology* 39, 344–354.

Chen, J., Frank Chen, F., 2008. Adaptive scheduling and tool flow control in flexible job shops. *International Journal of Production Research* 46, 4035–4059.

Chen, J.C., Wu, C.-C., Chen, C.-W., Chen, K.-H., 2012. Flexible job shop scheduling with parallel machines using genetic algorithm and grouping genetic algorithm. *Expert Systems with Applications* 39, 10016–10021.

Chiang, T.-C., Lin, H.-J., 2013. A simple and effective evolutionary algorithm for multiobjective flexible job shop scheduling. *International Journal of Production Economics* 141, 87–98.

Colorni, A., Dorigo, M., Maniezzo, V., Trubian, M., 1994. Ant system for job-shop scheduling. *Belgian Journal of Operations Research, Statistics and Computer Science* 34, 39–53.

Dalfard, V.M., Mohammadi, G., 2012. Two meta-heuristic algorithms for solving multi-objective flexible job-shop scheduling with parallel machine and maintenance constraints. *Computers & Mathematics with Applications* 64, 2111–2117.

Dauzère-Pérès, S., Paulli, J., 1997. An integrated approach for modeling and solving the general multiprocessor job-shop scheduling problem using tabu search. *Annals of Operations Research* 70, 281–306.

Davarzani, Z., Akbarzadeh-T, M.-R., Khairdoost, N., 2012. Multiobjective artificial immune algorithm for flexible job shop scheduling problem. *International Journal of Hybrid Information Technology* 5, 75–88.

Davoudpour, H., Azad, N., 2012. Solving multi-objective flexible job shop scheduling problems using immune algorithm. *International Journal of Modern Science and Technology* 13, 1–13.

De Giovanni, L., Pezzella, F., 2010. An improved genetic algorithm for the distributed and flexible job-shop scheduling problem. *European Journal of Operational Research* 200, 395–408.

Defersha, F.M., Chen, M., 2010. A parallel genetic algorithm for a flexible job-shop scheduling problem with sequence dependent setups. *International Journal of Advanced Manufacturing Technology* 49, 263–279.

Demir, Y., Kürşat İşleyen, S., 2013. Evaluation of mathematical models for flexible job-shop scheduling problems. *Applied Mathematical Modelling* 37, 977–988.

Doh, H.-H., Yu, J.-M., Kim, J.-S., Lee, D.-H., Nam, S.-H., 2013. A priority scheduling approach for flexible job shops with multiple process plans. *International Journal of Production Research* 51, 3748–3764.

Dorigo, M., 1992. *Optimization, Learning and Natural Algorithms*. Dipartimento di Elettronica. Politecnico di Milano, Milan, Italy.

Eberhart, R., Kennedy, J., 1995. A new optimizer using particle swarm theory. Proceedings of the Sixth International Symposium on Micro Machine and Human Science (MHS '95), Nagoya, Japan, October 4–6, pp. 39–43.

Elazeem, A.E.M.A., Osman, M.S.A., Hassan, M.B.A., 2011. Optimality of the flexible job shop scheduling problem. *African Journal of Mathematics and Computer Science Research* 4, 321–328.

Ennigrou, M., Ghédira, K., 2008. New local diversification techniques for flexible job shop scheduling problem with a multi-agent approach. *Autonomous Agents and Multi-Agent Systems* 17, 270–287.

Eykhoff, P., 1974. *System Identification: Parameter and State Estimation*. Wiley-Interscience, Chichester.

Fahmy, S.A., Elmekkawy, T.Y., Balakrishnan, S., 2007. Analysis of reactive deadlock-free scheduling in flexible job shops. *International Journal of Flexible Manufacturing Systems* 19, 264–285.

Farmer, J.D., Packard, N.H., Perelson, A.S., 1986. The immune system, adaptation, and machine learning. *Physica D* 22, 187–204.

Farughi, H., Yegane, B.Y., Fathian, M., 2013. A new critical path method and a memetic algorithm for flexible job shop scheduling with overlapping operations. *Simulation* 89, 264–277.

Farughi, H., Yegane, B.Y., Soltanpanah, H., Zaheri, F., Naseri, F., 2011. Considering the flexibility and overlapping in operation in job shop scheduling based on meta-heuristic algorithms. *Australian Journal of Basic and Applied Sciences* 5, 526–533.

Fattahi, P., Fallahi, A., 2010. Dynamic scheduling in flexible job shop systems by considering simultaneously efficiency and stability. *CIRP Journal of Manufacturing Science and Technology* 2, 114–123.

Fattahi, P., Jolai, F., Arkat, J., 2009. Flexible job shop scheduling with overlapping in operations. *Applied Mathematical Modelling* 33, 3076–3087.

Fattahi, P., Saidi-Mehrabad, M., Jolai, F., 2007. Mathematical modeling and heuristic approaches to flexible job shop scheduling problems. *Journal of Intelligent Manufacturing* 18, 331–342.

Feo, T.A., Resende, M.G.C., 1989. A probabilistic heuristic for a computationally difficult set covering problem. *Operations Research Letters* 8, 67–71.

Fliege, J., Drummond, L.M.G., Svaiter, B., 2009. Newton's method for multiobjective optimization. *SIAM Journal on Optimization* 20, 602–626.

French, S., 1982. *Sequencing and Scheduling: An Introduction to the Mathematics of the Job-Shop*. Ellis Horwood, Chichester.

Frutos, M., Olivera, A.C., Tohmé, F., 2010. A memetic algorithm based on a NSGAII scheme for the flexible job-shop scheduling problem. *Annals of Operations Research* 181, 745–765.

Gao, J., Gen, M., Sun, L., 2006. Scheduling jobs and maintenances in flexible job shop with a hybrid genetic algorithm. *Journal of Intelligent Manufacturing* 17, 493–507.

Gao, J., Gen, M., Sun, L., Zhao, X., 2007. A hybrid of genetic algorithm and bottleneck shifting for multiobjective flexible job shop scheduling problems. *Computers & Industrial Engineering* 53, 149–162.

Gao, K.Z., Suganthan, P.N., Pan, Q.K., Chua, T.J., Cai, T.X., Chong, C.S., 2014. Discrete harmony search algorithm for flexible job shop scheduling problem with multiple objectives. *Journal of Intelligent Manufacturing*, doi: 10.1007/s10845-014-0869-8.

Gao, J., Sun, L., Gen, M., 2008. A hybrid genetic and variable neighborhood descent algorithm for flexible job shop scheduling problems. *Computers & Operations Research* 35, 2892–2907.

Garey, M.R., Johnson, D.S., 1979. *Computers and Intractability: A Guide to the Theory of NP-Completeness*. W.H. Freeman, San Francisco , CA.

Gen, M., Lin, L., 2012. Multiobjective genetic algorithm for scheduling problems in manufacturing systems. *Industrial Engineering & Management Systems* 11, 310–330.

Geyik, F., Dosdoğru, A., 2013. Process plan and part routing optimization in a dynamic flexible job shop scheduling environment: an optimization via simulation approach. *Neural Computing and Applications* 23, 1631–1641.

Gholami, M., Zandieh, M., 2009. Integrating simulation and genetic algorithm to schedule a dynamic flexible job shop. *Journal of Intelligent Manufacturing* 20, 481–498.

Giffler, B., Thompson, G.L., 1960. Algorithms for solving production-scheduling problems. *Operations Research* 8, 487–503.

Girish, B.S., Jawahar, N., 2009. Scheduling job shop associated with multiple routings with genetic and ant colony heuristics. *International Journal of Production Research* 47, 3891–3917.

Glover, F., 1986. Future paths for integer programming and links to artificial intelligence. *Computers & Operations Research* 13, 533–549.

Golenko-Ginzburg, D., Laslo, Z., 2004. Chance constrained oriented dispatching rules for flexible job-shop scheduling. *Computer Modelling & New Technologies* 8, 14–18.

Gomes, M.C., Barbosa-Póvoa, A.P., Novais, A.Q., 2005. Optimal scheduling for flexible job shop operation. *International Journal of Production Research* 43, 2323–2353.

Gomes, M.C., Barbosa-Póvoa, A.P., Novais, A.Q., 2013. Reactive scheduling in a make-to-order flexible job shop with re-entrant process and assembly: a mathematical programming approach. *International Journal of Production Research* 51, 5120–5141.

Grobler, J., Engelbrecht, A.P., Kok, S., Yadavalli, S., 2010. Metaheuristics for the multi-objective FJSP with sequence-dependent set-up times, auxiliary resources and machine down time. *Annals of Operations Research* 180, 165–196.

Gutiérrez, C., García-Magariño, I., 2011. Modular design of a hybrid genetic algorithm for a flexible job-shop scheduling problem. *Knowledge-Based Systems* 24, 102–112.

Ham, M., Lee, Y.H., Kim, S.H., 2011. Real-time scheduling of multi-stage flexible job shop floor. *International Journal of Production Research* 49, 3715–3730.

Hansmann, R.S., Rieger, T., Zimmermann, U.T., 2013. Flexible job shop scheduling with blockages. *Mathematical Methods of Operations Research* 79, 135–161.

Hart, E., Ross, P., Nelson, J., 1998. Producing robust schedules via an artificial immune system. IEEE International Conference on Evolutionary Computation Proceedings and IEEE World Congress on Computational Intelligence, Anchorage, AK, May 4–9, pp. 464–469.

He, W., Sun, D.-H., 2013. Scheduling flexible job shop problem subject to machine breakdown with route changing and right-shift strategies. *International Journal of Advanced Manufacturing Technology* 66, 501–514.

He, W., Sun, D., Liao, X., 2013. Applying novel clone immune algorithm to solve flexible job shop problem with machine breakdown. *Journal of Information and Computational Science* 10, 2783–2797.

Hmida, A.B., Haouari, M., Huguet, M.-J., Lopez, P., 2010. Discrepancy search for the flexible job shop scheduling problem. *Computers & Operations Research* 37, 2192–2201.

Ho, N.B., Tay, J.C., 2008. Solving multiple-objective flexible job shop problems by evolution and local search. *IEEE Transactions on Systems, Man, and Cybernetics, Part C* 38, 674–685.

Ho, N.B., Tay, J.C., Lai, E.M.K., 2007. An effective architecture for learning and evolving flexible job-shop schedules. *European Journal of Operational Research* 179, 316–333.

Huang, R.-H., Yang, C.-L., Cheng, W.-C., 2013. Flexible job shop scheduling with due window—a two-pheromone ant colony approach. *International Journal of Production Economics* 141, 685–697.

Hurink, J., Jurisch, B., Thole, M., 1994. Tabu search for the job-shop scheduling problem with multi-purpose machines. *Aerospace Science and Technology Operations Research Spektrum* 15, 205–215.

Ida, K., Oka, K., 2011. Flexible job-shop scheduling problem by genetic algorithm. *Electrical Engineering in Japan* 177, 28–35.

Imanipour, N., Zegordi, S.H., 2006. A heuristic approach based on tabu search for early/tardy flexible job shop problems. *Scientia Iranica* 13, 1–13.

Jalilvand-Nejad, A., Fattahi, P., 2013. A mathematical model and genetic algorithm to cyclic flexible job shop scheduling problem. *Journal of Intelligent Manufacturing*, doi: 10.1007/s10845-013-0841-z.

Jang, Y.-J., Kim, K.-D., Jang, S.-Y., Park, J., 2003. Flexible job shop scheduling with multi-level job structures. *JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing* 46, 33–38.

Jansen, K., Mastrolilli, M., Solis-Oba, R., 2005. Approximation algorithms for flexible job shop problems. *International Journal of Foundations of Computer Science* 16, 361–379.

Jensen, M.T., 2003. Generating robust and flexible job shop schedules using genetic algorithms. *IEEE Transactions on Evolutionary Computation* 7, 275–288.

Jia, S., Hu, Z.-H., 2014. Path-relinking tabu search for the multi-objective flexible job shop scheduling problem. *Computers & Operations Research* 47, 11–26.

Jiang, J., Wen, M., Ma, K., Long, X., Li, J., 2011. Hybrid genetic algorithm for flexible job-shop scheduling with multi-objective. *Journal of Information and Computational Science* 8, 2197–2205.

Kacem, I., Hammadi, S., Borne, P., 2002a. Approach by localization and multiobjective evolutionary optimization for flexible job-shop scheduling problems. *IEEE Transactions on Systems, Man, and Cybernetics, Part C* 32, 1–13.

Kacem, I., Hammadi, S., Borne, P., 2002b. Pareto-optimality approach for flexible job-shop scheduling problems: hybridization of evolutionary algorithms and fuzzy logic. *Mathematics and Computers in Simulation* 60, 245–276.

Kantorovich, L.V., 1940. A new method of solving some classes of extremal problems. *Doklady Akad Sci USSR* 28, 211–214.

Karaboga, D., 2005. *An Idea Based on Honey Bee Swarm for Numerical Optimization*. Computer Engineering Department, Erciyes University, Kayseri.

Karimi, H., Rahmati, S.H.A., Zandieh, M., 2012. An efficient knowledge-based algorithm for the flexible job shop scheduling problem. *Knowledge-Based Systems* 36, 236–244.

Kennedy, J., Eberhart, R., 1995. Particle swarm optimization. IEEE International Conference on Neural Networks, Perth, Australia, Nov. 29–Dec. 1, pp. 1942–1948.

Khalife, M.A., Abbasi, B., Abadi, A.K.D., 2010. A simulated annealing algorithm for multiobjective flexible job shop scheduling with overlapping in operations. *Journal of Optimization in Industrial Engineering* 3, 17–28.

Kim, Y.K., Park, K., Ko, J., 2003. A symbiotic evolutionary algorithm for the integration of process planning and job shop scheduling. *Computers & Operations Research* 30, 1151–1171.

Kirkpatrick, S., Vecchi, M.P., 1983. Optimization by simmulated annealing. *Science* 220, 671–680.

Kis, T., 2003. Job-shop scheduling with processing alternatives. *European Journal of Operational Research* 151, 307–332.

Lan, M., Xu, T.-R., Peng, L., 2010. Solving flexible multi-objective JSP problem using a improved genetic algorithm. *Journal of Software* 5, 1107–1113.

Lee, S., Moon, I., Bae, H., Kim, J., 2012. Flexible job-shop scheduling problems with 'AND'/'OR' precedence constraints. *International Journal of Production Research* 50, 1979–2001.

Lei, D., 2010. A genetic algorithm for flexible job shop scheduling with fuzzy processing time. *International Journal of Production Research* 48, 2995–3013.

Lei, D., 2012. Co-evolutionary genetic algorithm for fuzzy flexible job shop scheduling. *Applied Soft Computing* 12, 2237–2245.

Lei, D., Guo, X., 2011. Swarm-based neighbourhood search algorithm for fuzzy flexible job shop scheduling. *International Journal of Production Research* 50, 1639–1649.

Lei, D., Guo, X., 2014. Variable neighbourhood search for dual-resource constrained flexible job shop scheduling. *International Journal of Production Research* 52, 2519–2529.

Li, L., Huo, J.-Z., 2009. Multi-objective flexible job-shop scheduling problem in steel tubes production. *Systems Engineering* 29, 117–126.

Li, J.-Q., Pan, Q.-K., 2012. Chemical-reaction optimization for flexible job-shop scheduling problems with maintenance activity. *Applied Soft Computing* 12, 2896–2912.

Li, J.-Q., Pan, Q.-K., Chen, J., 2011a. A hybrid Pareto-based local search algorithm for multi-objective flexible job shop scheduling problems. *International Journal of Production Research* 50, 1063–1078.

Li, J.-Q., Pan, Q.-K., Gao, K.-Z., 2011b. Pareto-based discrete artificial bee colony algorithm for multi-objective flexible job shop scheduling problems. *International Journal of Advanced Manufacturing Technology* 55, 1159–1169.

Li, J.-Q., Pan, Q.-K., Liang, Y.-C., 2010a. An effective hybrid tabu search algorithm for multi-objective flexible job-shop scheduling problems. *Computers & Industrial Engineering* 59, 647–662.

Li, J.-Q., Pan, Q.-K., Suganthan, P.N., Chua, T.J., 2011c. A hybrid tabu search algorithm with an efficient neighborhood structure for the flexible job shop scheduling problem. *International Journal of Advanced Manufacturing Technology* 52, 683–697.

Li, J.-Q., Pan, Q.-K., Tasgetiren, M.F., 2014. A discrete artificial bee colony algorithm for the multi-objective flexible job-shop scheduling problem with maintenance activities. *Applied Mathematical Modelling* 38, 1111–1132.

Li, J., Pan, Q., Xie, S., 2010b. A hybrid variable neighborhood search algorithm for solving multi-objective flexible job shop problems. *Computer Science and Information Systems* 7, 907–930.

Li, J., Pan, Q., Xie, S., 2012. An effective shuffled frog-leaping algorithm for multi-objective flexible job shop scheduling problems. *Applied Mathematics and Computation* 218, 9353–9371.

Li, J.-Q., Pan, Q.-K., Xie, S.-X., Jia, B.-X., Wang, Y.-T., 2010c. A hybrid particle swarm optimization and tabu search algorithm for flexible job-shop scheduling problem. *International Journal of Computer Theory and Engineering* 2, 189–194.

Li, J.-Q., Pan, Q.-K., Xie, S.-X., Wang, Y.-T., 2008. An effective hybrid particle swarm optimization algorithm for flexible jobshop scheduling problem. *International Journal of Advanced Engineering Applications* 1, 9–13.

Li, J.-Q., Pan, Q.-K., Xie, S.-X., Wang, S., 2011d. A hybrid artificial bee colony algorithm for flexible job shop scheduling problems. *International Journal of Computers Communications & Control* 6, 286–296.

Liouane, N., Saad, I., Hammadi, S., Borne, P., 2007. Ant systems & local search optimization for flexible job shop scheduling production. *International Journal of Computers Communications & Control* 2, 174–184.

Liu, H., Abraham, A., Wang, Z., 2009. A multi-swarm approach to multi-objective flexible job-shop scheduling problems. *Fundamenta Informaticae* 95, 465–489.

Liu, X., Zhang, G., 2012. A flexible job shop online scheduling approach based on process-tree. *Journal of Theoretical and Applied Information Technology* 44, 259–264.

Loukil, T., Teghem, J., Fortemps, P., 2007. A multi-objective production scheduling case study solved by simulated annealing. *European Journal of Operational Research* 179, 709–722.

Mahdavi, I., Shirazi, B., Solimanpur, M., 2010. Development of a simulation-based decision support system for controlling stochastic flexible job shop manufacturing systems. *Simulation Modelling Practice and Theory* 18, 768–786.

Mastrolilli, M., Gambardella, L.M., 2000. Effective neighbourhood functions for the flexible job shop problem. *Journal of Scheduling* 3, 3–20.

Mati, Y., Lahlou, C., Dauzère-Pérès, S., 2011. Modelling and solving a practical flexible job-shop scheduling problem with blocking constraints. *International Journal of Production Research* 49, 2169–2182.

Mekni, S., Chaâr, B.F., Ksouri, M., 2011. Flexible job-shop scheduling with TRIBES-PSO approach. *Journal of Computing* 3, 97–105.

Mekni, S., Chaâr, B.F., Ksouri, M., 2012. TRIBES-PSO approach applied to the flexible job shop scheduling problem. *Journal of Modelling and Simulation of Systems* 3, 35–41.

Mesghouni, K., Pesin, P., Trentesaux, D., Hammadi, S., Tahon, C., Borne, P., 1999. Hybrid approach to decision-making for job-shop scheduling. *Production Planning & Control* 10, 690–706.

Mladenović, N., Hansen, P., 1997. Variable neighborhood search. *Computers & Operations Research* 24, 1097–1100.

Moradi, E., Fatemi Ghomi, S.M.T., Zandieh, M., 2010. An efficient architecture for scheduling flexible job-shop with machine availability constraints. *International Journal of Advanced Manufacturing Technology* 51, 325–339.

Moradi, E., Fatemi Ghomi, S.M.T., Zandieh, M., 2011. Bi-objective optimization research on integrated fixed time interval preventive maintenance and production for scheduling flexible job-shop problem. *Expert Systems with Applications* 38, 7169–7178.

Moslehi, G., Mahnam, M., 2011. A Pareto approach to multi-objective flexible job-shop scheduling problem using particle swarm optimization and local search. *International Journal of Production Economics* 129, 14–22.

Motaghedi-Larijani, A., Sabri-Laghaie, K., Heydari, M., 2010. Solving flexible job shop scheduling with multiobjective approach. *International Journal of Industrial Engineering & Production Research* 21, 197–209.

Mousakhani, M., 2013. Sequence-dependent setup time flexible job shop scheduling problem to minimise total tardiness. *International Journal of Production Research* 51, 3476–3487.

Na, H., Park, J., 2014. Multi-level job scheduling in a flexible job shop environment. *International Journal of Production Research* 52, 3877–3887.

Nagamani, M., Chandrasekaran, E., Saravanan, D., 2012. Single objective evolutionary algorithm for flexible job-shop scheduling problem. *International Journal of Mathematics Trends and Technology* 3, 78–81.

Nagamani, M., Chandrasekaran, E., Saravanan, D., 2013. Pareto-based hybrid multi-objective evolutionary algorithm for flexible job-shop scheduling problem. *IOSR Journal of Mathematics* 9, 35–45.

Nicoara, E.S., Filip, F.G., Paraschiv, N., 2011. Simulation-based optimization using genetic algorithms for multi-objective flexible JSSP. *Studies in Informatics and Control* 20, 333–344.

Nie, L., Gao, L., Li, P., Li, X., 2013. A GEP-based reactive scheduling policies constructing approach for dynamic flexible job shop scheduling problem with job release dates. *Journal of Intelligent Manufacturing* 24, 763–774.

Ow, P.S.I., Morton, T.E., 1988. Filtered beam search in scheduling. *International Journal of Production Research* 26, 35–62.

Özgüven, C., Özbakır, L., Yavuz, Y., 2010. Mathematical models for job-shop scheduling problems with routing and process plan flexibility. *Applied Mathematical Modelling* 34, 1539–1548.

Özgüven, C., Yavuz, Y., Özbakır, L., 2012. Mixed integer goal programming models for the flexible job-shop scheduling problems with separable and non-separable sequence dependent setup times. *Applied Mathematical Modelling* 36, 846–858.

Pandian, P.P., Sankar, S.S., Ponnambalam, S.G., Raj, V., 2012. Scheduling of automated guided vehicle and flexible jobshop using jumping genes genetic algorithm. *American Journal of Applied Sciences* 9, 1706–1720.

Pansuwan, P., Rukwong, N., Pongcharoen, P., 2010. Identifying optimum artificial bee colony (ABC) algorithm's parameters for scheduling the manufacture and assembly of complex products. Second International Conference on Computer and Network Technology (ICCNT), Bangkok, April 23–25, pp. 339–343.

Pérez, M.A.F., Raupp, F.M.P., 2014. A Newton-based heuristic algorithm for multi-objective flexible job-shop scheduling problem. *Journal of Intelligent Manufacturing*, doi: 10.1007/s10845-014-0872-0.

Pezzella, F., Morganti, G., Ciaschetti, G., 2008. A genetic algorithm for the flexible job-shop scheduling problem. *Computers & Operations Research* 35, 3202–3212.

Pongchairerks, P., Kachitvichyanukul, V., 2009. A particle swarm optimization algorithm on job-shop scheduling problems with multi-purpose machines. *Asia-Pacific Journal of Operational Research* 26, 161–184.

Rabiee, M., Zandieh, M., Ramezani, P., 2012. Bi-objective partial flexible job shop scheduling problem: NSGA-II, NRGA, MOGA and PAES approaches. *International Journal of Production Research* 50, 7327–7342.

Rahmati, S.H.A., Zandieh, M., 2011. A new biogeography-based optimization (BBO) algorithm for the flexible job shop scheduling problem. *International Journal of Advanced Manufacturing Technology* 58, 1115–1129.

Rahmati, S.H.A., Zandieh, M., Yazdani, M., 2013. Developing two multi-objective evolutionary algorithms for the multi-objective flexible job shop scheduling problem. *International Journal of Advanced Manufacturing Technology* 64, 915–932.

Rajabinasab, A., Mansour, S., 2010. Dynamic flexible job shop scheduling with alternative process plans: an agent-based approach. *International Journal of Advanced Manufacturing Technology* 54, 1091–1107.

Rajkumar, M., Asokan, P., Anilkumar, N., Page, T., 2011. A GRASP algorithm for flexible job-shop scheduling problem with limited resource constraints. *International Journal of Production Research* 49, 2409–2423.

Rajkumar, M., Asokan, P., Vamsikrishna, V., 2010. A GRASP algorithm for flexible job-shop scheduling with maintenance constraints. *International Journal of Production Research* 48, 6821–6836.

Resende, M.G.C., Ribeiro, C.C., 2010. Greedy randomized adaptive search procedures: advances, hybridizations, and applications. In Gendreau, M., Potvin, J.-Y. (eds) *Handbook of Metaheuristics*. Springer, New York, pp. 283–291.

Roshanaei, V., Azab, A., Elmaraghy, H., 2013. Mathematical modelling and a meta-heuristic for flexible job shop scheduling. *International Journal of Production Research* 51, 6247–6274.

Rossi, A., Dini, G., 2007. Flexible job-shop scheduling with routing flexibility and separable setup times using ant colony optimisation method. *Robotics and Computer-Integrated Manufacturing* 23, 503–516.

Saad, I., Hammadi, S., Benrejeb, M., Borne, P., 2008. Choquet integral for criteria aggregation in the flexible job-shop scheduling problems. *Mathematics and Computers in Simulation* 76, 447–462.

Sadaghiani, J.S., Boroujerdi, S.A., Mirhabibi, M., Sadaghiani, P.S., 2014. A Pareto archive floating search procedure for solving multi-objective flexible job shop scheduling problem. *Decision Science Letters* 3, 157–168.

Sadrzadeh, A., 2013. Development of both the AIS and PSO for solving the flexible job shop scheduling problem. *Arabian Journal for Science and Engineering* 38, 3593–3604.

Saidi-Mehrabad, M., Fattahi, P., 2007. Flexible job shop scheduling with tabu search algorithms. *International Journal of Advanced Manufacturing Technology* 32, 563–570.

Scrich, C.R., Armentano, V.A., Laguna, M., 2004. Tardiness minimization in a flexible job shop: a tabu search approach. *Journal of Intelligent Manufacturing* 15, 103–115.

Shahsavari-Pour, N., Ghasemishabankareh, B., 2013. A novel hybrid meta-heuristic algorithm for solving multi objective flexible job shop scheduling. *Journal of Manufacturing Systems* 32, 771–780.

Shao, X., Liu, W., Liu, Q., Zhang, C., 2013. Hybrid discrete particle swarm optimization for multi-objective flexible job-shop scheduling problem. *International Journal of Advanced Manufacturing Technology* 67, 2885–2901.

Sharma, N.K., 2013. Optimization of flexible jobshop scheduling problem using attribute oriented mining. *International Journal of Scientific & Engineering Research* 4, 1809–1819.

Shi-Jin, W., Bing-Hai, Z., Li-Feng, X., 2008. A filtered-beam-search-based heuristic algorithm for flexible job-shop scheduling problem. *International Journal of Production Research* 46, 3027–3058.

Sun, D.-H., He, W., Zheng, L.-J., Liao, X.-Y., 2014. Scheduling flexible job shop problem subject to machine breakdown with game theory. *International Journal of Production Research* 52, 3858–3876.

Sun, W., Pan, Y., Lu, X., Ma, Q., 2010. Research on flexible job-shop scheduling problem based on a modified genetic algorithm. *Journal of Mechanical Science and Technology* 24, 2119–2125.

Taghavi-Fard, M.T., Saidy, H.R.D., 2009. Flexible job shop scheduling under availability constraints. *Journal of Industrial Engineering International* 5, 52–60.

Tanev, I.T., Uozumi, T., Morotome, Y., 2004. Hybrid evolutionary algorithm-based real-world flexible job shop scheduling problem: application service provider approach. *Applied Soft Computing* 5, 87–100.

Tavakkoli-Moghaddam, R., Shahsavaripour, N., Mohammadi-Andargoli, H., Abolhasani-Ashkezari, M.H., 2012. Duplicate genetic algorithm for scheduling a bi-objective flexible job shop problem. *International Journal of Research in Industrial Engineering* 1, 10–26.

Tay, J.C., Ho, N.B., 2008. Evolving dispatching rules using genetic programming for solving multi-objective flexible job-shop problems. *Computers & Industrial Engineering* 54, 453–473.

Tereshko, V., Loengarov, A., 2005. Collective decision making in honey-bee foraging dynamics. *Computing and Information Systems* 9, 1–7.

Thomalla, C.S., 2001. Job shop scheduling with alternative process plans. *International Journal of Production Economics* 74, 125–134.

Torabi, S.A., Karimi, B., Fatemi Ghomi, S.M.T., 2005. The common cycle economic lot scheduling in flexible job shops: the finite horizon case. *International Journal of Production Economics* 97, 52–65.

Vaghefinezhad, S., Wong, K.Y., 2012. A genetic algorithm approach for solving a flexible job shop. *International Journal of Computer Science Issues* 9, 85–90.

Vilcot, G., Billaut, J.-C., 2011. A tabu search algorithm for solving a multicriteria flexible job shop scheduling problem. *International Journal of Production Research* 49, 6963–6980.

Wang, X., Gao, L., Zhang, C., Shao, X., 2010. A multi-objective genetic algorithm based on immune and entropy principle for flexible job-shop scheduling problem. *International Journal of Advanced Manufacturing Technology* 51, 757–767.

Wang, L., Wang, S., Liu, M., 2013a. A Pareto-based estimation of distribution algorithm for the multi-objective flexible job-shop scheduling problem. *International Journal of Production Research* 51, 3574–3592.

Wang, L., Wang, S., Xu, Y., Zhou, G., Liu, M., 2012a. A bi-population based estimation of distribution algorithm for the flexible job-shop scheduling problem. *Computers & Industrial Engineering* 62, 917–926.

Wang, Y.M., Yin, H.L., Qin, K.D., 2013b. A novel genetic algorithm for flexible job shop scheduling problems with machine disruptions. *International Journal of Advanced Manufacturing Technology* 68, 1317–1326.

Wang, S., Yu, J., 2010. An effective heuristic for flexible job-shop scheduling problem with maintenance activities. *Computers & Industrial Engineering* 59, 436–447.

Wang, L., Zhou, G., Xu, Y., Liu, M., 2012b. An enhanced Pareto-based artificial bee colony algorithm for the multi-objective flexible job-shop scheduling. *International Journal of Advanced Manufacturing Technology* 60, 1111–1123.

Wang, L., Zhou, G., Xu, Y., Liu, M., 2013c. A hybrid artificial bee colony algorithm for the fuzzy flexible job-shop scheduling problem. *International Journal of Production Research* 51, 3593–3608.

Wang, L., Zhou, G., Xu, Y., Wang, S., Liu, M., 2012c. An effective artificial bee colony algorithm for the flexible job-shop scheduling problem. *International Journal of Advanced Manufacturing Technology* 60, 303–315.

Wu, Z., Weng, M.X., 2005. Multiagent scheduling method with earliness and tardiness objectives in flexible job shops. *IEEE Transactions on Systems, Man, and Cybernetics, Part B* 35, 293–301.

Xia, W., Wu, Z., 2005. An effective hybrid optimization approach for multi-objective flexible job-shop scheduling problems. *Computers & Industrial Engineering* 48, 409–425.

Xing, L.-N., Chen, Y.-W., Wang, P., Zhao, Q.-S., Xiong, J., 2010. A knowledge-based ant colony optimization for flexible job shop scheduling problems. *Applied Soft Computing* 10, 888–896.

Xing, L.-N., Chen, Y.-W., Yang, K.-W., 2008. Double layer ACO algorithm for the multi-objective FJSSP. *New Generation Computing* 26, 313–327.

Xing, L.-N., Chen, Y.-W., Yang, K.-W., 2009a. An efficient search method for multi-objective flexible job shop scheduling problems. *Journal of Intelligent Manufacturing* 20, 283–293.

Xing, L.-N., Chen, Y.-W., Yang, K.-W., 2009b. Multi-objective flexible job shop schedule: design and evaluation by simulation modeling. *Applied Soft Computing* 9, 362–376.

Xing, L.-N., Chen, Y.-W., Yang, K.-W., 2011. Multi-population interactive coevolutionary algorithm for flexible job shop scheduling problems. *Computational Optimization and Applications* 48, 139–155.

Xiong, J., Tan, X., Yang, K.-W., Xing, L.-N., Chen, Y.-W., 2012. A hybrid multiobjective evolutionary approach for flexible job-shop scheduling problems. *Mathematical Problems in Engineering* 2012, 1–27.

Xiong, J., Xing, L.-N., Chen, Y.-W., 2013. Robust scheduling for multi-objective flexible job-shop problems with random machine breakdowns. *International Journal of Production Economics* 141, 112–126.

Xu, X., Li, L., Fan, L., Zhang, J., Yang, X., Wang, W., 2013. Hybrid discrete differential evolution algorithm for lot splitting with capacity constraints in flexible job scheduling. *Mathematical Problems in Engineering* 2013, 1–10.

Yazdani, M., Amiri, M., Zandieh, M., 2010. Flexible job-shop scheduling with parallel variable neighborhood search algorithm. *Expert Systems with Applications* 37, 678–687.

Yazdani, M., Gholami, M., Zandieh, M., Mousakhani, M., 2009. A simulated annealing algorithm for flexible job shop scheduling problem. *Journal of Applied Sciences* 9, 662–670.

Yegane, B.Y., Khanlarzade, N., Fard, A.R., 2012. Memetic algorithm for flexible job shop scheduling with preemption. *International Journal of Industrial Engineering & Production Management* 22, 331–340.

Yuan, Y., Xu, H., 2013a. Flexible job shop scheduling using hybrid differential evolution algorithms. *Computers & Industrial Engineering* 65, 246–260.

Yuan, Y., Xu, H., 2013b. An integrated search heuristic for large-scale flexible job shop scheduling problems. *Computers & Operations Research* 40, 2864–2877.

Yuan, Y., Xu, H., 2013c. Multiobjective flexible job shop scheduling using memetic algorithms. *IEEE Transactions on Automation Science and Engineering* 12, 1–18.

Yuan, Y., Xu, H., Yang, J., 2013. A hybrid harmony search algorithm for the flexible job shop scheduling problem. *Applied Soft Computing* 13, 3259–3272.

Yulianty, A., Ma'ruf, A., 2013. Predictive approach on flexible job shop scheduling problem considering controllable processing times. *International Journal of Innovation, Management and Technology* 4, 565–569.

Zambrano Rey, G., Bekrar, A., Prabhu, V., Trentesaux, D., 2014. Coupling a genetic algorithm with the distributed arrival-time control for the JIT dynamic scheduling of flexible job-shops. *International Journal of Production Research* 52, 3688–3709.

Zandieh, M., Mahdavi, I., Bagheri, A., 2008. Solving the flexible job-shop scheduling problem by a genetic algorithm. *Journal of Applied Sciences* 8, 4650–4655.

Zhang, G., Gao, L., Shi, Y., 2011. An effective genetic algorithm for the flexible job-shop scheduling problem. *Expert Systems with Applications* 38, 3563–3573.

Zhang, H., Gen, M., 2005. Multistage-based genetic algorithm for flexible job-shop scheduling problem. *Journal of Complexity International* 11, 223–232.

Zhang, L., Li, X., Wen, L., Zhang, G., 2013. An efficient memetic algorithm for dynamic flexible job shop scheduling with random job arrivals. *International Journal of Software Science and Computational Intelligence* 5, 63–77.

Zhang, Q., Manier, H., Manier, M.A., 2012. A genetic algorithm with tabu search procedure for flexible job shop scheduling with transportation constraints and bounded processing times. *Computers & Operations Research* 39, 1713–1723.

Zhang, G., Shao, X., Li, P., Gao, L., 2009. An effective hybrid particle swarm optimization algorithm for multi-objective flexible job-shop scheduling problem. *Computers & Industrial Engineering* 56, 1309–1318.

Zheng, Y.-L., Li, Y.-X., Lei, D.-M., 2012. Multi-objective swarm-based neighborhood search for fuzzy flexible job shop scheduling. *International Journal of Advanced Manufacturing Technology* 60, 1063–1069.

Zhou, D., Zeng, L., 2013. A flexible job-shop scheduling method based on hybrid genetic annealing algorithm. *Journal of Information and Computational Science* 10, 5541–5549.

Ziaee, M., 2013. A heuristic algorithm for solving flexible job shop scheduling problem. *International Journal of Advanced Manufacturing Technology* 71, 519–528.

Zribi, N., Kacem, I., El Kamel, A., Borne, P., 2007. Assignment and scheduling in flexible job-shops by hierarchical optimization. *IEEE Transactions on Systems, Man, and Cybernetics, Part C* 37, 652–661.