# Six Decades of Flowshop Scheduling Research

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**Abstract**— In the field of scheduling, the flowshop problems have been thoroughly studied over the last six decades. In this paper we propose a concise overview of flowshop scheduling techniques evolved during this period. We surveyed the exact, heuristics and metaheuristics methods for solving various flowshop scheduling problems. As a result various optimization techniques, solution procedures are available to solve a variety of problems. We also present a brief glimpse of the evolution of flowshop scheduling problems and possible approaches for their solutions. This paper also concludes with some fruitful directions for the future research.

**Index Terms**— Flowshop Scheduling; Exact, Heuristics and Meta-Heuristics Methods; Future Research Directions.

## 1 Introduction

Scheduling has been a subject of a significant amount of literature in the operations research field since the early 1950s. The main objective of scheduling is an efficient allocation of shared resources over time to competing activities. It is convenient to adopt manufacturing terminology, where *jobs* represent activities and *machines* represent resources, while the range of application areas for scheduling theory is not limited to computers and manufacturing but includes transportation, services, etc. The terms "sequencing" and "scheduling" are usually used interchangeably. However, distinguishing them is useful. Convey et al. [86] claim that whenever there is a choice as to the order in which a number of tasks can be performed, there will be a sequencing problem. Baker [61] discusses the sequencing problem as a specialized scheduling problem in which the ordering of jobs completely determines a schedule. The first scientific publications on production scheduling appeared more than half a century ago. However, many authors have recognized a gap between the literature and the industrial problems Initial research concerning flow shop scheduling problem was done by Johnson [96]. Johnson described an exact algorithm to minimize makespan for the *n*-jobs two-machine flow shop scheduling problem. Later, algorithms, such as branch-andbound and beam search, that yield the exact solution for this problem were proposed. The flow shop scheduling problem of minimizing makespan is a classical combinatorial optimization problem for the NP-hard problem class (Garey et al., [72]). The flow shop scheduling problem that includes many jobs and machines is a combinatorial

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optimization problem for the NP-

hard problem category. Therefore, near optimum solution techniques are preferred. Several heuristic approaches for the flowshop scheduling problem are developed.

In recent years, metaheuristic approaches, such as simulated annealing, tabu search, and genetic algorithms, have become very desirable in solving combinatorial optimization problems because of their computational performance.

The metaheuristic is a rather general algorithmic framework that can be applied to different optimization problems with minor modifications. By considering recent studies on the flow shop scheduling problem, it is obvious that solution methods based on metaheuristic approaches are frequently proposed.

## 2 Flowshop Scheduling Problem

The flowshop scheduling has been a very active and prolific research area since the seminal paper of Johnson [96]. The flowshop scheduling problem is a production problem where a set of $n$ jobs have to be processed with identical flow pattern on $m$ machines. When the sequence of job processing on all machines in the same order we have the permutation flowshop sequencing production environment. The work-flow in a flowshop is unidirectional. This means that the order in which jobs are processed on various machines is the same for all n jobs and is specified

### 2.1 Flowshop assumptions-

Gupta et al. [52] describes the following 21 assumptions for the traditional flowshop scheduling problem originally conceived in Johnson [96] paper.

#### *2.1.1 Assumptions concerning job*

J1. Each job is released to the shop at the beginning of the scheduling period.

J2. Each job may have its own due date which is fixed and is not subject to change.

J3. Each job is independent of each other.

J4. Each job consists of specified operations, each of which is performed by only one machine.

J5. Each job has a prescribed technological order which is the same for all jobs and is fixed.

J6. Each job (operation) requires a known and finite processing time to be processed by various machines. This processing time includes transportation and setup times, if any, and is independent of preceding and succeeding jobs.

J7. Each job is processed no more than once on any machine.

J8. Each job may have to wait between machines and thus in-process inventory is allowed.

#### *2.1.2 Assumptions concerning machines*

M1. Each machine center consists of only one machine; that is, the shop has only one machine of each type.

M2. Each machine is initially idle at the beginning of the scheduling period.

M3. Each machine in the shop operates independently of other machines and thus is capable of operating at its own maximum output rate.

M4. Each machine can process at most one job at a time. This eliminates those machines that are designed to process several jobs simultaneously like multi-spindle drill.

M5. Each machine is continuously available for processing jobs throughout the scheduling period and there are no interruptions due to breakdowns, maintenance or other such caues.

#### *2.1.3 Assumptions concerning operating policies*

P1. Each job is processed as early as possible. Thus, there is no intentional job waiting or machine idle time.

P2. Each job is considered an indivisible entity even though it may be composed of a number of individual units.

P3. Each job, once accepted, is processed to completion; that is, no cancellation of jobs is permitted.

P4. Each job (operation), once started on a machine, is completed to its completion before another job can start on that machine, that is, no preemptive priorities are assigned.

P5. Each job is processed on no more than one machine at a time. (This is a result of assumptions J5 and P2.)

P6. Each machine is provided with adequate waiting space for allowing jobs to wait before starting their processing.

P7. Each machine is fully allocated to the jobs under consideration for the entire scheduling period; that is, machines are not used for any other purpose throughout the scheduling period.

P8. Each machine processes jobs in the same sequence. That is, no passing or overtaking of jobs is permitted.

## 3 Briefly Study of Flowshop Scheduling Research During Last Six Decades: 1952-2011

### 3.1 First Decades (1952-1961)

Since the first studies on scheduling by Salveson [68]. After the publication of Johnson's classical paper on the two- machine flowshop scheduling problem, developments in the first decade include the consideration of the m-machine flowshop problem to minimize makespan. Early research on the flowshop problem was highly theoretical, and it tended toward optimization techniques such as mathematical programming Thus, this decade saw consideration of mathematical programming approaches to flowshop problems on one hand and the use of Monte-Carlo simulation techniques on the other (for a review of these developments, see Sisson [87]. it began the analytical framework for the development of dominance conditions for flowshop scheduling.

### 3.2 Second decade (1962–1971)

Only a few solution techniques were developed during last decade because of these three reasons: (1) lack of computer power; (2) lack of efficient computer programs; and, more importantly, (3) most variants of the two-machine flowshop problem are NP-hard. The combinatorial approach that Johnson used for the two-machine problem was extended to the m-machine flowshop problem by Dudek and Teuton [84]. The second decade witnessed a rather wide range of solution techniques on one hand and the consideration of objective functions other than makespan on the other hand. The combinatorial approach started by Dudek and Teuton [84] was corrected and improved by Smith and Dudek [85], McMahon [36], Gupta [52], and Szwarc ([118], [119]). The branch and bound solution approaches were also developed during this time by Lomnicki (1965), Brown and Lomnicki [7], McMahon and Burton [67], Gupta ([51], [54]), and others. Except for the papers by Ignall and Schrage [29] and Gupta [55], all these papers consider makespan as the optimality criterion.

### 3.3 Third decade (1972–1981)

The emergence of the theory of NP-completeness (which is now called NP-hardness) had a profound impact on the direction of developments in flowshop scheduling (see Garey and Johnson [73] for a detailed study of NP-hardness). On one hand, there are developments to resolve the complexity status of various flowshop scheduling problems (see Brucker [81], Chen et al. [8], Lawler et al. [30] and Pinedo [71] for reviews of complexity of scheduling problems); on the other hand, many more heuristic approaches were developed during this time (see the book by Morton and Pentico [103] for various heuristic approaches). This decade witnessed the consideration of flowshop scheduling problems with separable setup times on the other. Further, this decade also witnessed the consideration of due date related objective functions in flowshop scheduling (see Mortonand Pentico [103] for these developments).

### 3.4 Fourth decade (1982–1991)

This decade saw the emergence of hybrid flowshops where each stage of the flowshop could contain multiple parallel machines and the development of metaheuritics like Tabu Search, Genetic Algorithms, and Simulated Annealing (see Aarts and Lenstra [26], Osman and Kelly [41]. This decdes expansion of efforts to solve flowshop problems with separable setups which could be either sequence independent or sequence dependent (see the reviews by Chenget al. [102]). Nagar et al. [4] proposed a B&B procedure for solving a two machine flowshop problem with a weighted combination of flowtime and makespan as objective. Cavalieri and Gaiardelli [92] study a realistic production problem that they modelize as a flowshop

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problem with makespan and tardiness criteria. This decade also witnessed the use of artificial intelligence based techniques to solve the flowshop scheduling problems.

### 3.5 Fifth decade (1992–2001)

The proliferation of the variety of flowshop scheduling problems, objective functions, and solution approaches continued in this decade. While it is difficult to identify any one single problem as being representative of developments during this decade that was not considered earlier, it is interesting to note that consideration and solution of multi-criteria flowshop scheduling became quite popular in this decade (see T'Kindt and Billaut [112] for a review of multi-criteria scheduling problems). This decade did witness expanded attention on the simultaneous consideration of lot sizing and scheduling on one hand and the batch processing machines on the other (see Potts and Kovalyov [14] and Trietsch and Baker [25] as examples of these developments). In Neppalli et al. [116] two genetic algorithms were proposed for solving the two machine bicriteria flowshop problem also in a lexicographical way as in Rajendran [17].

### 3.6 Sixth Decades (2002-2011)

This decade had seen several developments and improvements to the already identified and evolved flowshop problems. Gupta et al. [57] proposed nine heuristics for the two machine case minimizing flowtime subject to optimum makespan, i.e., Lex(Cmax, F) Ruiz et al. [90] investigate the effectiveness and efficiency of various metaheuristics in minimizing makespan in flowshops with separated sequence dependent setup times (SDST). These heuristics are adaption of existing metaheuritics for the regular flowshop to SDST flowshop. In addition to testing existing algorithms, these authors also propose and compare two advanced genetic algorithms for solving the SDST flowshop problem. This decade also saw significant progress in developing solution procedures for robotic flowshops and flowshops equipped with automatic guided vehicles (AGVs) as is evident from the recent review by Geismar et al. [39]. These methods and many other less known heuristics are well-reviewed in Framinan et al. [50]. Ruiz and Maroto [90] give an updated and comprehensive review of flow shop heuristics and metaheuristics. Another recent review is given by Reza Hejazi and Saghafian [99]. The literature in which the flow shop scheduling problem is modeled as a traveling salesman problem (TSP) is reviewed by Bagchi et al. [109] Gupta and Stafford [56] provide the developments in flow shop scheduling over the last 50 years. Recent reviews and comparative evaluations of heuristics and metaheuristics for this problem are given in Framinan et al.[50] Ruiz and Maroto [90]. A recent review for the total tardiness version of the PFSP can be found in Vallada et al. [31]. Zitzler et al. [32] present a much more extensive notation which is later extended in Luis [83] and more recently in Knowles et al. [48]. Review by T'kindt and Billaut [113] we find about 15 flowshop papers reviewed where most of them are about the specific two machine case. Another review is given by Jones et al. [19]. Finally, the more recent review of Hoogeveen [38] contains mainly results for one machine and parallel machines scheduling problems. Lin and Wu [9] focuses on the two machine case with a weighted combination of makespan and flowtime. Lemesre et al. [49] have studied the $m$ machine problem with makespan and total tardiness criteria.

## 4 Survey of Exact, Heuristic and Meta heuristic methods during last 60 years

Flowshop scheduling problem categorized as NP hard problem and it means development of heuristic and meta-heuristic approaches to solve it is well justified. Several methods have been used to solve combinatorial optimization problem but each having its own limitation and advantages. Classification of common combinatorial optimization can be broadly classified into two, firstly, the exact methods and secondly approximate methods (Heuristics and Metaheuristics). Several heuristic approaches for the flowshop scheduling problem are developed. In recent years, metaheuristic approaches, such as Simulated Annealing, Tabu Search, and Genetic Algorithms, Ant Colony Optimization algorithms etc. have become very desirable in solving combinatorial optimization problems because of their computational performance. Here we survey the Exact, Heuristics and Meta heuristic methods for flowshop scheduling problems during last 60 years.

### 4.1 Classification of Methodology to Solve Combinatorial Optimization Problems

The flow shop scheduling problem that includes many jobs and machines is a combinatorial optimization problem for the NP-hard problem category. It is known that the decision making associated with the scheduling problem belongs to the category of combinatorial optimization problems. The range of techniques that have been applied to tackle combinatorial optimization problems can be classified in two general category, firstly, the exact methods and secondly the approximate (heuristic) methods. Exact methods seek to solve a problem to guaranteed optimality but their execution on large real world problems usually requires too much computation time. Consequently, resolution by exact methods is not realistic for large problems, justifying the use of powerful heuristic and metaheuristics methods.

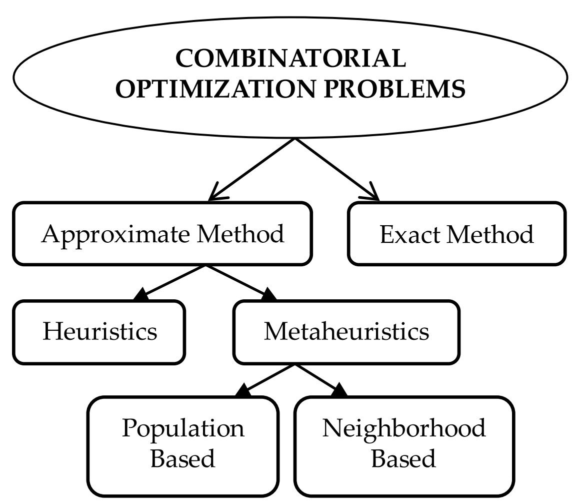


Fig.1 Classification of Methodology to solve Combinatorial Optimization problems

For practical use heuristic methods seek to find high quality solutions (not necessarily optimal) within reasonable computation times. Metaheuristics are a class of heuristic techniques that have been successfully applied to solve a wide range of combinatorial optimization problems over the years (Voss et al., [101]; Osman and Laporte, [41]). We classified the different methods for solving combinatorial optimization problems in fig.1

## 4.2 Exact Techniques

Several exact techniques have been used for regular or non-regular performance measures for flow shop scheduling. Yet theoretical analysis is far from satisfaction due to its complexity and there exists neither a universally accepted technique nor an analytical algorithm for solving such NP Hard problems. Traditional optimization techniques have been successfully applied to flow shop scheduling problems with simple settings (Pinedo, [70]) but have drawback of long computational time as being exact techniques. The complexity of flow shop scheduling problems, using exact methods to solve them is impracticable for instances of more than a few jobs and/or machines. One of the exact techniques to obtain an optimal solution is the straightforward enumeration where every possible solution is explored in order to find the optimal solution. However, due the computational complexity, it is not practical even for problems of moderate sizes. Another exact technique is the branch and bound technique where the known upper bounds or lower bounds for the solution are used to restrict the search space. The efficiency of these algorithms is dependent on the quality of the lower bounds.

- The first branch and bound algorithms developed by Ignall and Schrage [29] for the permutation flow-shop problem with makespan minimization.
- Lockett and Muhlemann [3] proposed branch and bound algorithm for scheduling jobs with sequence dependent setup times on a single processor to minimize the total number of tool changes.
- Gupta [55] presented a mathematical model based on the branch and bound technique to solve static scheduling problems involving n jobs and m machines for minimize the cost of setting up the machines as objective.
- Gupta [53] proposed a branch and bound algorithm to minimize setup cost in '*n*' jobs and '*m*' machines flow shop with sequence dependent setup times.
- Sen et al. [111] proposed a branch and bound algorithm for the two machine flow shop problem.
- Another branch and bound algorithm for the two-machine case is that of Kim [121]. Kim proposed a branch and bound to compute a lower bound with objective of total tardiness objective in flow shop scheduling.
- Carlier et al. [45] propose two branch and bound algorithms for the permutation flow shop problem.
- Pan and Fan [3] also presented a branch and bound for the same problem.
- Lee and Wu [117] considered the two-machine flow shop scheduling problem to minimize the bi-criterion objectives of completion time and tardiness.
- Pan et al. [44] also proposed another branch and bound algorithm for the two machine case in which several procedures to establish precedence constraints between jobs were presented.
- Toktas et al. [114] considered the two machine flow shop scheduling for minimizing makespan and maximum earliness simultaneously using a branch and bound procedure.
- Temiz et al. [42] developed a modified branch and bound algorithm for a three machine flow-shop sequencing problem.
- Ladhari et al. [108] reviewed some of the existing branch and bound algorithms and the various lower bound computations.
- In the work of Schaller [59], three branch and bound algorithms were developed with improved lower bound and the dominance conditions as presented by Pan et al. [44] and a new dominance rule was also proposed.

## 4.3 Heuristic Algorithms

Heuristic algorithms can be broadly classified into dispatching rules, constructive and improvement heuristics. Constructive heuristics build a schedule from scratch by making a series of passes through the list of unscheduled jobs where at each pass one or more jobs are selected and added to the schedule. Contrary to constructive heuristics, improvement heuristics start from an existing solution and apply some improvement procedure. In constructive heuristics, once a sequence is obtained, it is fixed and cannot be altered whereas in improvement heuristics, an initial solution is iteratively improved upon.

### *4.3.1 Dispatching Rules*

Dispatching rules are a very common means of scheduling due to their simplicity, speed, and predictability of speed in arriving at a solution. Dispatching rules are also often implemented without an expert system. The biggest drawback of many dispatching rules is the quality of the solution. There is no guarantee of even a local optimum, much less a global optimum. A second drawback is that there is no straightforward means to tell how far the solution is from the global optimum. Panwalkar et al. [100] gives a more detailed explanation of some of these dispatching rules. Some of the rules, especially EDD, SLACK and EWDD are common for total tardiness and total weighted tardiness minimization.

### *4.3.2 Constructive and Improvement Heuristics*

Since the flow-shop problem is a NP-hard problem with computations being prohibitively expensive, a practical approach is to use heuristic methods to obtain near optimal solutions. Johnson first studied the two-machine problem with the objective of minimizing makespan [96]. This approach basically divides the jobs into two categories and sequences them from left to right and right to left respectively. It is also referred to as the (SPT (1)-LPT (2)) problem where SPT is the Shortest Processing Time and LPT stands for Largest Processing Time. Many researchers have generalized this to 'm' machines.

- Palmer [24] proposed ranking of jobs based on a slope index computed from the processing times there by giving preference to jobs that tend to progress from low to high processing times.
- Gupta [52] modified Palmer's slope index based on the principle of sorting *n* items based on a heuristic.
- Dannenbring [20] developed a procedure called rapid access. It attempts to combine the advantages of Palmers slope index and the CDS methods.
- Gelders and Sambandom [62] proposed four simple heuristics for the sum of weighted tardiness s criterion.
- Nawaz et al. [79] developed NEH heuristic for the permutation flow shop scheduling problem with the makespan minimization criterion for *m* machines and *n* jobs.
- In this, jobs are sorted in non-increasing order of the sum of processing times on all machines and considered best to till date for makespan minimization in flow shop scheduling.
- Kim [121] sorted the jobs following the EDD rule, that is, in non-decreasing order of due dates.
- Rajendran and Chaudhuri [15] have proposed a heuristic algorithm to minimize flow time for a flow-shop scheduling problem using three heuristic criteria.
- Raman [78] adapted several rules and heuristic algorithms for the single machine and two-machine cases and evaluated for the multi-machine flow shop problem.
- Danneberg et al. [20] proposed and compared various constructive and iterative heuristic algorithms for permutation flow shop scheduling problem including setup times with objective function of weighted sum of makespan and completion times of the jobs. These heuristics have confirmed good results but limited to 120 job problems.
- Ronconi [21] developed a MinMax (MM) algorithm which also addresses the flow shop makespan minimization problem with no buffers.
- Kalczyncski et al. [82] proposed a construction heuristic for minimizing the makespan in a no-idle permutation flow-shop.
- Chakraborty and Laha [115] modified the original NEH algorithm for makespan minimization problem in permutation flow shop scheduling.
- Dulluri et al. [93] developed a priority based heuristic for minimizing the makespan for a turbine manufacturing industry. This heuristic produced optimal schedule based on the dynamic priorities of the customer work orders.
- Eren [104] considered a bi-criteria *m*-machine flow shop scheduling with sequence dependent setup times with minimization of the weighted sum of total completion time and makespan. He developed the special heuristics similar to NEH (Nawaz et al., [79]) for fitness function considered and proved that the special heuristic for all number of jobs and machines was more effective than the others.

## 4.4 METAHEURISTICS

Metaheuristics are general heuristic methods that guide the search through the solution space, using as surrogate algorithms some form of heuristics and usually local search.

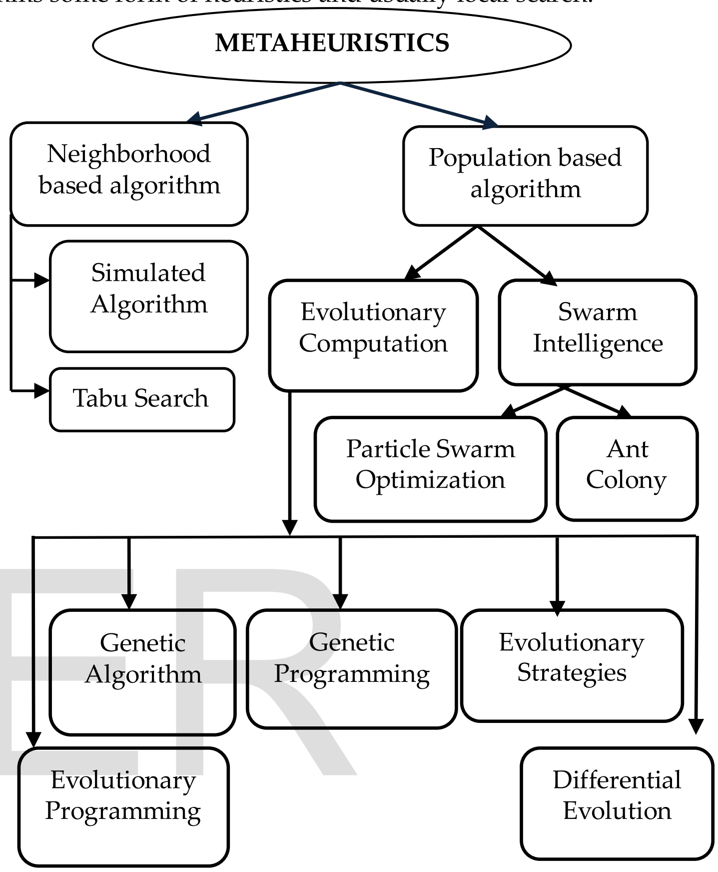


Fig. 2 Classification of Metaheuristics

Starting from an initial solution built by some heuristic, metaheuristics improve it iteratively until a stopping criterion is met. The stopping criterion can be elapsed time, number of iterations and number of evaluations of the objective function and so on.

- Voss et al. [101] described a metaheuristic as "*Iterative master processes that guides and modifies the operations of subordinate heuristics to efficiently produce high quality solutions*".

Osman et al. [41] provide an extensive bibliography on metaheuristics and its applications in combinatorial optimization problems. Some of the widely researched metaheuristic algorithms include adaptive search techniques like genetic algorithm (GA), artificial immune system (AIS) and neural networks, neighborhood search techniques like simulated annealing (SA), and tabu search, and their hybrid versions.

### 4.4.1 Tabu Search

Tabu Search (TS) is a robust local search based optimization method that begins with an initial solution and successively moves to the best solution in the neighborhood of the current solution while maintaining a list of attributes of solutions to prevent the algorithm from visiting solutions already examined.

- Nowicki propose a fast tabu search algorithm with reduced neighborhood search using a modified NEH algorithm to obtain the initial solution.
- Ben-Daya proposed a tabu search heuristic with a mechanism of combining the intensification and diversification schemes that improves the performance of the TS approach.
- Brucker et al. [81] have proposed a tabu search algorithm for cyclic machine scheduling problems with specific application to job-shops
- Fred Choobineh proposed tabu search heuristic with makespan, weighted tardiness and number of tardiness simultaneously including sequence dependent setup for n jobs.

### 4.4.2 Genetic Algorithm

Genetic Algorithm (GA) based algorithms, inspired by Darwin's theory of natural selection and survival of the fittest, were invented by Holland and first proposed for scheduling problems by Goldberg.

- One of the earliest GA for the flow shop scheduling was proposed by Chen et al. [13] to minimize makespan for a flow shop scheduling problem in which initial population was generated by using several heuristic rules.
- Cavalieri and Gaiardell [92] developed two hybrid genetic algorithms (GAs) for allocation and sequencing of production lots in a flow shop environment based on a nonlinear, multi-criteria objective function of makespan and mean tardiness.
- Wu et al. [117] considered flow shop scheduling problem with parallel machine and special procedure constraint.
- Ravindran et al. [23] proposed three new hybrid algorithms (HAMC1, HAMC2, and HAMC3) based on the GA approach to minimize makespan and total flow time in a flow-shop scheduling problem.
- Tang and Liu [65] proposed a modified GA algorithm (MGA) to minimize the mean flow time for a flow-shop scheduling problem.
- Gaafar et al. [67] proposed modified genetic algorithm inspired by the particle swarm optimization approach to solve the scheduling problem of a manufacturing system consisting of machining and assembly stages, with the objective of minimizing the makespan.
- Tseng and Lin [102] developed hybrid genetic local search algorithm for the permutation flow shop scheduling problem with the total flow time (makespan) criterion.
- Erenay et al. [104] solved bi-criteria scheduling problem with minimization of the number of tardy jobs and average flow time on a single machine.

### 4.4.3 Simulated Annealing

Simulated Annealing (SA) algorithms, based on the analogy of annealing process of metals, were proposed by Metropolis et al. [77] and were first applied to combinatorial optimization problems by Kirkpatrick. SA is considered to be an improvement heuristic where a given initial solution is iteratively improved upon. A number of researchers have applied SA to scheduling problems. Some of them include:

- Osman and Potts [49] propose a set of four different SA based heuristic algorithms for the flow-shop problem and have shown that their algorithms yield better results compared to NEH algorithm which is currently the best construction heuristic for flow-shop sequencing problems.
- Ogbu and Smith [33, 34] proposed a modified SA based heuristic algorithm using constructive heuristics to obtain initial solution and a novel acceptance probability function.
- Marett and Wright [88] compared the performance of tabu search and simulated annealing for multi-objective flow shop scheduling problems and found that results obtained by using simulated annealing were better than tabu search.
- Parthasarathy and Rajendran [97] considered simulated annealing heuristic for scheduling to minimize total weighted tardiness in a flow shop with sequence dependent set up times.
- Chakravarthy and Rajendran [115] have proposed a simulated annealing based heuristic for the m-machine flow-shop scheduling problem with bi-criteria minimization of makespan and maximum tardiness.
- Naderi et al. [10] proposed novel simulated annealing for hybrid flow shop scheduling problem to minimize total completion time and total tardiness including sequence dependent set up.

### 4.4.4 Neural Networks

- Neural network-based models are mathematical models that are based on the biological nervous systems and their adaptive behavior. The network consists of layers of interconnected nodes or neurons. Typically, there are at least two layers, an input layer and an output layer. One of the most common networks is the Back Propagation Network (BPN) which consists of an input layer, and an output layer with one or more intermediate hidden layers. One of the training algorithms used is the Back-Propagation algorithm (BP). Lee and Shaw [117] extended their work to two performance measures for optimization makespan and total flow time using the ANN approach.
- Akyol [18] used BPN network to model six different heuristic algorithms for the permutation flow-shop sequencing problem with unlimited buffer space associated with each machine.
- El-Bouri et al. [2] proposed neural networks to enhance local search in a permutation flow-shop scheduling problem.
- Tang et al. [65] also proposed a neural network-based model and algorithm for a hybrid flow-shop with dynamic job arrivals.

- Noorul Haq and Radha Ramanan [5] used Artificial Neural Network (ANN) for minimizing bi-criteria of makespan and total flow time in flow shop scheduling environment.

#### *4.4.5 Ant Colony Optimization*

Ant Colony Optimization (ACO) algorithms are population-based search algorithms based on the food hunting patterns of real ants that utilize agents (ants), single or multiple, to construct the optimal solution iteratively. The trails serve the purpose of remembering the previous solutions and have to be updated at the end of each iteration. Rajendran and Ziegler (2004) considering the problem of scheduling in permutation flow shops by using two ACO algorithms with the objective of minimizing the sum of the total flow time of jobs and makespan.

- Ying and Liao [60] have developed a meta-heuristic based on ACO for the permutation flow shop scheduling by modeling the system using disjunctive graphs.
- Shyu et al. [94] developed an ACO-based algorithm to solve the two machine flow shop scheduling problem with no waiting between operations and including set up time.
- Rajendran and Ziegler [16] proposed two ACO-based algorithms to minimize the total flow time in permutation flow-shops.
- Yagmahan and Yenisey [12] introduced ant colony optimization for minimizing multi-objectives including makespan, total flow time and total machine idle time.
- Zhou et al. [91] proposed ant colony optimization for dynamic jobs scheduling Problems.
- Yagmahan and Yenise [16] considered the flow shop scheduling problem with respect to minimization of both objectives of makespan and total flow time and the proposed algorithm based on ACS metaheuristic called as a multi-objective ant colony system algorithm (MOACSA).

#### *4.4.6 Artificial Immune Systems*

Artificial immune system (AIS) is an adaptive heuristic technique inspired by the human immune system. The immune system consists of mainly lymphocytes. There are two types of lymphocytes viz. the ones that originate and develop in the bone marrow (Bcells), and the ones that originate in the bone marrow and move to the thymus to grow (Tcells). Both these cells have receptors on their surface that attach themselves to disease causing pathogens thereby triggering the immune response. The two integral aspects in the immune response mechanism are the clonal selection principle and the affinity maturation the detailed account of which can be found in De Castro and Timmis [63].

Although both AIS and GA-based methods are population-based and evolutionary Algorithms Engin and Doyen [80] propose an AIS-based heuristic for hybrid flow shops.

### 4.5 Miscellaneous and Hybrid Metaheuristics

The use of metaheuristics has received more and more attention in the last 30 years. The first two decades of research on metaheuristics were characterized by the application of rather standard metaheuristics. However, in recent years it has become evident that the concentration on a sole metaheuristic is rather restrictive. A skilled combination of a metaheuristic with other optimization techniques, a so called *hybrid metaheuristic*, can provide a more efficient behavior and a higher flexibility when dealing with real-world and large-scale problems. This can be achieved, for instance, by combining the complementary strengths of metaheuristics on one side and of complete methods such as branch & bound techniques or mathematical programming on the other side. In general, hybrid metaheuristic approaches can be classified as either *collaborative combinations* or *integrative combinations* (see [47, 27]). Collaborative combinations are based on the exchange of information between several optimization techniques run sequentially (or in parallel). This kind of combination is more related to cooperative and parallel search and we forward the interested reader to the specific literature on the subject [113, 46, 64, 56, 112, 111, and 119]. Most contributions of this book deal with interesting and representative cases of integrative combinations.

- Talbi [28] gives a detailed classification framework and taxonomy of hybrid metaheuristics. The author also provides an extensive bibliography of literature in this area.
- Noorul Haq et al. [5] proposed a hybrid heuristic based on Ant System (AS) and GA approaches to minimize the makespan for a flow-shop scheduling problem.
- Lawler et al. [30] proposed a heuristic algorithm that combines the benefits of SAbased algorithms and TS-based algorithms.
- Nearchou [1] proposes a hybrid SA-based algorithm which incorporates features from GA based and local search heuristics.
- Solimanpur et al. [74] proposed a tabu search (EXTS) algorithm based on neural networks for permutation flow-shop scheduling problem.
- Ravindran et al. [22] used multi-criterion approach to flow shop scheduling problems by considering makespan time and total flow time as objectives to be minimized.
- Tseng and Lin [66] proposed a hybrid genetic algorithm for the flow-shop scheduling problem.
- Rahimi Vahed and Mirghorbani [89] developed multi-objective particle swarm optimization to minimize the weighted mean completion time and weighted mean tardiness simultaneously in flow shop scheduling environment.
- Naderi [11] et al. considered SDST hybrid flow shop scheduling to minimize makespan and maximum tardiness.

## 5 Conclusions

This paper contains a complete and updated review of the literature for multi objective flowshop problems. Exact, heuristic and metaheuristic methods have been surveyed. In this

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paper we have conducted a comprehensive survey of the multi-objective literature for the flowshop, one of the most common and thoroughly studied problems in the scheduling field. The papers surveyed include exact as well as heuristic techniques for many different multi-objective approaches. This paper has provided a brief excursion into the developments in flowshop scheduling theory during the last sixty years. Several optimization, heuristics, metaheuristics and hybrid metaheuristics solution procedures are available to solve a variety of flowshop scheduling problems. This paper provides a brief glimpse into the evolution of flowshop scheduling problems and possible approaches for their solution over the last sixty years.

## 6 Directions for Future Research

In spite of several developments in the last sixty years, even the theoretical flowshop scheduling problem remains largely unsolved. Further studies can focus on the sensitivity and parameter studies and their possible relationships with the convergence rate of the algorithm. Hybridization with other popular algorithms such as PSO will also be potentially fruitful. The future research directions suggested here are intended to bridge the gap between the development of theory and practical applications of theory. Three areas of research are identified: theoretical, computational, and empirical research.

### 6.1 Theoretical research

Theoretical research in flowshop scheduling should attempt to develop dominance conditions that are either independent of partial schedules that precede a job candidate or are such that a large number of partial schedules containing a lesser number of jobs are rejected quickly. The dominance conditions developed (in combinatorial and branch and bound procedures) depend on partial schedules that precede a job candidate. Theoretical research should consider many more special cases of flowshop scheduling that have been considered before and develop efficient optimization techniques for their solution. Simultaneously, quicker, perhaps dirty but reliable heuristic procedures should be developed. Consideration of hybrid heuristic approaches for these problems provides another fruitful area for future theoretical research.

### 6.2 Computational Research

A practical scheduler has difficulty in selecting an algorithm to solve a given flowshop scheduling problem. The computational research should consider such aspects as comparative efficiency of various algorithms for a specified problem with given data set. Thus, new measures of computational effort required should be developed.

In addition, artificial intelligence techniques, such as neural networks should be further exploited to select specific heuristics to be used for a given problem (see Gupta et al. (2000) for one such effort).

### 6.3 Empirical Research

Future research in flowshop scheduling should be inspired more by real life problems rather than problems encountered in mathematical abstractions. For a realistic problem formulation, empirical research is necessary to understand the practical situations. The flowshop scheduling is only one of a few areas where no case histories are available. Empirical research should answer such questions as: What is the maximum problem size encountered in practice? What specific situations give rise to flowshop scheduling problems? What are the desired objectives of scheduling? What is the nature of processing times? How rigid (or flexible) are the operating policies? Empirical research, therefore, needs to include a survey of industrial scheduling practices and situations. Without such a survey, we may in fact spend another twenty-five years in solving a problem that perhaps needs no solution, since it may be the wrong problem (from practical consideration).

We believe study remains to be done in the following areas: It is a good idea to use flow shop specific techniques to speed up the convergence of the algorithm. Algorithms can be developed to optimize population size, number of generations and percentages of genetic operators. New genetic operators can be developed to increase the evolution and convergence speed The recent developments in supply chain management, internet, and e-commerce have created new and complex scheduling and coordination problems that we have just begun to understand. Therefore, we need to diversify our research efforts in scheduling to include these new and emerging problems.

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