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RESEARCH STUDY OF STATE-OF-THE-ART ALGORITHMS FOR FLEXIBLE JOB-SHOP SCHEDULING PROBLEM

PRZEGLĄD WSPÓŁCZESNYCH ALGORYTMÓW HARMONOGRAMOWANIA ZADAŃ Z MASZYNAMI ALTERNATYWNYMI

A b s t r a c t

The paper discusses various approaches used to solve flexible job-shop scheduling problem concentrating on formulations proposed in the last ten years. It mainly refers to the applied metaheuristic techniques which have been exploited in this research area. A comparison of presented approaches is attempted, some concluding insights are highlighted. Finally future research directions are suggested.

Keywords: *flexible job-shop scheduling*, *multi-objective optimization*, *review*

S t r e s z c z e n i e

W artykule opisano różne podejścia stosowane do rozwiązania problemu harmonogramowania zadań z maszynami alternatywnymi. Skoncentrowano się na opracowaniach opublikowanych w ostatnich dziesięciu latach. Głównie skupiono uwagę na podejściach wykorzystujących algorytmy metaheurystyczne. Dokonano próby porównania merytorycznego dostępnych w literaturze rozwiązań oraz wskazano kierunki dalszych prac.

Słowa kluczowe: *harmonogramowanie zadań z maszynami alternatywnymi*, *optymalizacja wielokryterialna*, *przegląd literatury*

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1. Introduction

One of the most popular research problem that is exploited in recent years by international research centres is job-shop scheduling problem. Because of its combinatorial complex nature of sequencing operations on available machines, it is quite difficult to obtain optimal solution directed to specific criterion. Therefore, many evolutionary approaches emerged in order to cope with this problem. These approaches provide sub-optimal satisfactory solutions with the emphasis on, in the most cases, one chosen criterion achieved in deterministic conditions [1]. It is worth noticing that optimization process runs with considering many constraints. One of them is that an operation can be processed only on one machine.

As an extension of this problem, flexible job-shop scheduling (FJS) problem has increasingly focused research attention over last ten years. This is because of eliminating explicitly onerous constraint which does not permit doing operations on alternative machines. However, by the evolution to FJS problem, the level of computational complexity has been deepened significantly. The main reason is concerned to necessity of combining several optimization criteria such as minimizing the overall completion time (makespan), total workload of machines and the workload of the most loaded machine [2]. The need for developing new approaches in the domain of multi-objective optimization FJS problem has been intensified.

This paper is prepared for the investigation how modern research solve FJS problem. It is organized as follows. In section 2 the definition of flexibility of manufacturing systems is described. In section 3 problem definition and formulation is discussed. Section 4 presents solution methodologies for FJS problem and literature review based on the articles which were published over last ten years. Finally, summary and directions for future work is covered in section 5.

2. The definition of flexibility of manufacturing systems

The flexibility of manufacturing system can be defined as the ability of this system to adapt quickly to both the changeable demands of a market (demand uncertainty) or resources failures on the shopfloor (production uncertainty). This changeable conditions can be expressed by disturbances which result in lower efficiency of the manufacturing system. To cope with disturbances, management should identify and decide on the type and scope of flexibility corresponding to the manufacturing system. This can gain benefits in terms of increasing the value of total efficiency factor [3].

From the point of view of manufacturing systems, there is many kinds of flexibility which can be considered. Two of them are crucial, namely, a) the flexibility expressed by the possibility of machines rearrangement to produce part families according to group technology concept [4], b) the flexibility expressed by the possibility of machines to produce different parts without necessity to loss much time for reconfiguring machines [5]. Regarding the FJS problem, the second one is more interesting one.

In the study of ref. [6], two types of the second kind of flexibility have been investigated. Machine flexibility and routing flexibility have been selected and compared. According to the description from ref [6], machine flexibility is the capability of a machine to perform different

operations required by a given set of part types and includes quick machine setup and jig changing. This type of flexibility can be achieved by the use of high-tech automatic tool--changing or jig-changing devices in conjunction with sufficient tools and fixtures magazines as well as reconfigurable machines which allow to replace whole machine modules to perform other operations [7]. Machine flexibility allows smaller batch sizes, causing shorter lead times, higher machines utilization and reduced work-in-progress inventory level. Routing flexibility, in turn, is the capability of processing a given set of part types using more than one route (alternative routings) [8]. Routing flexibility assumes existence of alternative paths which can be followed through the manufacturing system for a given process plan [9].

Routing flexibility leads directly to the problem of FJS. This problem concerns two major steps: a) assignment of each operation to one of the alternative machines (as an assignment sub-problem), and b) sequencing the set of operations on each machine which has been previously assigned to perform these operations (as sequencing sub-problem) [10]. Routing flexibility can be improved by having identical machines or multipurpose machines. It can help to handle unplanned events such as machine breakdowns or rush orders [6].

FJS problem is strongly NP-hard. That's why it focus great attention by very large number of researchers. This paper describes only a handful of available research approaches which are available in literature. This approaches are mainly directed towards FJS problem with routing flexibility. The investigation has been conducted to find out the optimization methods used for solving multiobjective FJS problem, what is presented in the section 4.

3. Problem definition and formulation

FJS problem is an extension of the classical job-shop scheduling (JS) problem. In turn, job-shop scheduling is, next to single-machine scheduling, flow-shop scheduling and open-shop scheduling, one of the four basic problems, which have been classified as the challenging scheduling problems [11].

The classical JS problem considers N jobs to be processed on M machines assuming that they have pre-determined sequences of operations and each operation is performed on a predefined machine. It means that for each job, distinct routing is fixed and known in advance. In general, this problem is to determine optimal schedule of jobs so that one or more performance criteria could be achieved.

FJS problem is associated with two difficulties. The first one is to assign all operations to relevant machines (selected from $M_k \in M_{i,j}$). The second one is to calculate of the starting times of operations in order to determine appropriate (optimal) sequence of their execution on each machine so that technological constraints were not violated and predefined objectives could be obtained [12].

FJS problem belongs to class of NP-hard problems just as mentioned JS problem. This means that along with the growth of problem size, the number of calculations which must be done increase in an exponential manner, where N denotes problem size. It also is worth noticing that it has more complex nature than JS problem because of enlarged searching scope of potential solutions through reduce machine constraints. Bruker nad Schlie (1990) were among the first who took up solution of this problem [13].

FJS problem can be defined as follows [14]:
- there are N jobs independent from other jobs, indexed by i, $i = 1, \ldots, N$, where N denotes total number of jobs;
- each job consists of a sequence of operations, denotes by J_i (precedence constraints);
- there is the set of machines, indexed by M, $M = M_1, \ldots, M_k$, where M_k means total number machines in the set and k denotes k-th machine;
- each operation is indexed by $O_{i,j}$, $j = 1, \ldots, J_i$, where $O_{i,j}$ and J_i denote that J_i-th operation of job i and number of operations required for job i, respectively;
- each operation $O_{i,j}$ can be processed on only one machine out of a set of given machines which are able to perform it. The set of eligible machines is denoted by $M_{i,j}$ and $M_{i,j} \subseteq M$ (routing constraints);
- there is a predefined set of processing times. For a given operation $O_{i,j}$ and a given machine, the processing time is denoted by $t_{i,j,k}$;

moreover [14]:
- if each operation $O_{i,j}$ can be assigned to each machine from the set of available machines M, that is $M_{i,j} = M$, then it is called total flexibility FJS problem (T-FJS problem);
- if certain operations can be executed only by some machines from the set of available machines, that is $M_{i,j} \subset M$, then it is called partial flexibility FJS problem (P-FJS problem);

Additionally, the following assumptions are made during the process of solving this problem[14]:
- none of operation $O_{i,j}$ cannot be interrupted during its processing (non-preemption condition);
- each machine M_k can perform no more than one operation at any time (resource constraints);
- each machine is available to other operations immediately after operation which is assigned as the last to be completed;
- all machines are available at $t = 0$;
- all jobs can be started at $t = 0$;
- machines are independent from each other;
- there are no precedence constraints among operations of different jobs;
- setting up times of machines and transportation times between work stations (operations) are neglected;
- breakdowns are not considers;
- neither release times nor due dates are specified.

In the literature, the following performance criteria for FJS problem are often to be minimized [11]:
- maximal completion time, i.e. makespan $C_{\max}$;
- weight or mean completion time;
- maximal machine workload, i.e. sum of processing times of operations on a critical machine;
- total workload of machines, i.e. sum of working times over all machines;
- maximal tardiness;
- maximal lateness;

– maximum earliness;
– (weight) number of tardy jobs;
– maximal cost.

The most popular optimization criterion in the case of both single objective and multi-objective optimization of FJS problem is to minimize the makespan.

4. Solution methodologies for FJS problem

Due to the high complexity of FJS problem, we distinguish two classes of optimization approaches used to solve this problem. The first one is mathematical modeling while the second one is metaheuristic approach.

Mathematical modeling allows to obtain optimal solution for small size problems, in turn metaheuristic approach is used to solve medium and large size problems. Metaheuristic approaches allow to achieve near-optimal solution [12].

Taking mathematical models into considerations, there are three distinct ways of formulating the sequencing problem using integer programming (IP). These three approaches differ from each other the type of binary variable what stores information about sequence of operations on individual machines. Other existing formulations are based on these three groups of variables.

The first approach is based on the sequence-position variables. It was proposed by Wagner in 1959. The second one relies on precedence variables, introduced by Manne in 1960. The latter way is based on time-indexed variables, proposed by Bowman in 1959 [15].

The second class of optimization approaches directed towards solving FJS problem is involved with the use of metaheuristics. Over the past decade, metaheuristics have been intensively exploited for the combinational optimization of FJS problem. The FJS problem is considered to be more complex and difficult to obtain optimized solution than JS problem. Thus, many researchers willingly strive for metaheuristics and try to combine them applying hybridization in the way of achieving optimal solution. Five of the most notable groups of metaheuristics approaches using to solve FJS problem are: simulated annealing, tabu search, evolutionary algorithms, ant colony optimization and particle swarm optimization as well.

Simulated annealing (SA) and tabu search (TS) metaheuristics have a common characteristics as a search process starts from one initial state which is initial solution and follows through specific trajectory of solutions in order to find optimum one according to neighbor searching. One of the oldest metaheuristics is SA. In the case of FJS problem it is usually used to schedule operations on each machine after the process of assigning operations on machines [16]. That approach has been presented by Xia and Wu [17]. Fattahi et al. in turn proposed simulated annealing approach to solve FJS problem in the case if customer demand can be released more than one for each job as an important and practical issue of FJS problem [18]. Further, Dalfard and Mohammadi developed simulated annealing approach to solve FJS problem with parallel machines and with regard of maintenance cost [19].

TS algorithm has been used as a first metaheuristic to solve FJS problem [20]. Based on this approach more effective tabu search algorithm with advanced variable neighborhood

search has been developed [21]. It can be noticed, that after publication of ref. [20], tabu search has become frequently used metaheuristics to solve FJS problem. Henceforth, it has been frequently combined with other metaheuristics thereby forming hybrid approaches. The popular way is to combine tabu search with genetic algorithm, where tabu search is used to generate initial solution [22]. In other way, it can be used to solve more developed models like this with transportation constraints and bounded processing times [23].

The most exploited metaheuristics in terms of FJS problem is definitely genetic algorithms. It was first employed by well-known study of Kacem [24]. Pezzella et al. also solved FJS problem by genetic algorithm [25]. Further, Bagheri et al. followed by Pezzella et al. and proposed artificial immune algorithm to solve FJS problem [26].

The last group of approaches employs population- based methods, which are (except of mentioned genetic algorithms) particle swarm optimization (PSO) and ant colony optimization (ACO). As an example, Xing et al. proposed ACO algorithm to solve FJS problem [27], whereas Moslehi used particle swarm optimization for the same target [28].

5. Conclusions and future work directions

In the paper, FJS problem is considered and possible methods to solve it are presented. In addition, it is worth noting that despite the strong tendency to solve much more complex and difficult variants of JS problem, so far no algorithm has been developed what gives an optimal solution for the classical JS problem regardless of its size [29].

Since FJS problem is NP – hard problem, researches around the world focus their efforts on the developing effective metaheuristics that will find a good solution for a given optimal problem in acceptable time. In other words, metaheuristics attempt to achieve trade-off between solution quality and search completeness within reasonable a time interval.

The article briefly discussed the five most commonly used group of algorithms for multi--objective optimization FJS problem and possible their hybrids. Generally speaking, the hybrid algorithms as multi-objective optimization methods used to solve FJS problem are becoming more and more popular and it can be suggested as one of directions of further research.

Furthermore, it should be taken into account that in multi-objective problems with conflicting objective functions, existing only one (optimal) solution by optimizing all objective functions is almost impossible . Hence, in recent years, more studies have also focused on Pareto – based approaches what provide a set of optimal solutions, instead of a single optimal solution.

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