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Genetic tabu search for the fuzzy flexible job shop problem

Juan José Palacios [a], Miguel A. González [a], Camino R. Vela [a,*], Inés González-Rodríguez [b], Jorge Puente [a]

[a] Department of Computing, University of Oviedo, Spain
[b] Department of Mathematics, Statistics and Computing, University of Cantabria, Spain

A R T I C L E I N F O

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A B S T R A C T

This paper tackles the flexible job-shop scheduling problem with uncertain processing times. The uncertainty in processing times is represented by means of fuzzy numbers, hence the name fuzzy flexible job-shop scheduling. We propose an effective genetic algorithm hybridised with tabu search and heuristic seeding to minimise the total time needed to complete all jobs, known as makespan. To build a high-quality and diverse set of initial solutions we introduce a heuristic method which benefits from the flexible nature of the problem. This initial population will be the starting point for the genetic algorithm, which then applies tabu search to every generated chromosome. The tabu search algorithm relies on a neighbourhood structure that is proposed and analysed in this paper; in particular, some interesting properties are proved, such as feasibility and connectivity. Additionally, we incorporate a filtering mechanism to reduce the neighbourhood size and a method that allows to speed-up the evaluation of new chromosomes. To assess the performance of the resulting method and compare it with the state-of-the-art, we present an extensive computational study on a benchmark with 205 instances, considering both deterministic and fuzzy instances to enhance the significance of the study. The results of these experiments clearly show that not only does the hybrid algorithm benefit from the synergy among its components but it is also quite competitive with the state-of-the-art when solving both crisp and fuzzy instances, providing new best-known solutions for a number of these test instances.

1. Introduction

Scheduling operations is one of the most critical issues in manufacturing and production systems as well as in information processing environments [1]. The job-shop scheduling problem (*JSP*) is a simplified model of many problems in this class which has interested researchers for decades due to its simple formulation but, at the same time, high difficulty, being NP-hard [2]. In the classical *JSP* a set of jobs have to be processed on a set of machines, each job consisting of a sequence of consecutive operations and each operation requiring the exclusive use of exactly one machine during all its processing time, which is perfectly known in advance. A typical performance indicator is the makespan, i.e., the time required to complete all jobs.

Unfortunately, the classical *JSP* cannot model many practical situations due to the fact that project decisions usually have to be made in advance, when activity durations are still highly uncertain. A great variety of approaches have been considered to deal with these real-life situations, as can be seen in the review of fundamental approaches for scheduling under uncertainty from [3]. Maybe, the best-known approach is stochastic scheduling, where uncertain processing times are taken to be stochastic variables. A recent example can be found in [4], where a stochastic programming approach for the project scheduling is proposed. Here, the uncertainty of the durations is represented using a set of discrete scenarios in which each scenario has a probability of occurrence. The durations of activities are random variables which are supposed to be independent and for which the individual distributions can be estimated. More recently, in [5] a method for solving the resource constrained project scheduling problem with uncertain activity durations is given, where uncertain durations are described by independent random variables with a known probability distribution function. However, it is sometimes the case that probability distributions underlying durations are unknown and there is a lack of statistical data to validate the choice of duration distributions. It may even be argued that probability distributions allow us to model the variability of repetitive tasks, but not uncertainty due to a lack of information [6]. Even when durations are independent random variables it is admitted that estimating the makespan distribution

* Corresponding author.
E-mail addresses: palaciosjuan@uniovi.es (J.J. Palacios), mig@uniovi.es (M.A. González), crvela@uniovi.es (C.R. Vela), gonzalezri@unican.es (I. González-Rodríguez), puente@uniovi.es (J. Puente).

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is, in general, intractable [7]. An alternative and complementary approach to modelling ill-known processing times is to use fuzzy numbers or, more generally, fuzzy intervals in the setting of possibility theory. Fuzzy intervals share some of the disadvantages of probability theory, in particular the need of providing the possibility distribution that represents ill-known durations. However for, say, triangular fuzzy numbers the expert needs to only provide an interval of possible values and the most typical value, which is usually easier than accurately defining a probability distribution. Quantitative possibility theory is said to provide a natural framework, simpler and less data-demanding than probability theory, for handling incomplete knowledge about scheduling data. The fuzzy approach has been around for more than two decades and has received the attention of several researchers (cf. [8,9]). In particular, considerable effort has been made to solve the *fuzzy JSP* (*FJSP*), where task durations are modelled as fuzzy numbers (most commonly, triangular fuzzy numbers). Some of the existing approaches will be reviewed in Section 2.

Another characteristic of real-world problems is flexibility, which is contemplated in the *flexible JSP* (*fJSP* in short), a variant of the *JSP* where multiple machines can perform the same operation (possibly with different processing times). This flexibility allows the system to absorb changes in the demand of work or in the performance of the machines. On the other hand, it also increases the difficulty of the problem, since a solution must also consider the assignment of jobs to machines (job routings) in addition to scheduling operations on the machines.

Fuzzy processing times and flexibility on the machines can be considered simultaneously, as done for example in [10]. When this is the case, we have the *fuzzy flexible job-shop scheduling problem* (*FfJSP*). This will be the problem considered in this paper, with the objective of minimising the makespan.

As a solving method, we propose to design a hybrid algorithm combining a genetic algorithm with a local search strategy. This is motivated by the success of this hybridisation not just for solving JSP [11] but also for solving several extensions of it such as *JSP* with setup times [12], *FJSP* [13] or *fJSP* [14]. It is not possible however to directly apply these existing methods to *FfJSP*, because the addition of both flexibility and fuzzy processing times to the problem changes its nature, and therefore well-known results, both theoretical and empirical, regarding existing neighbourhood structures are no longer applicable in the new setting of *FfJSP*. We need new neighbourhood structures specific for this problem, with the corresponding study of their properties. The benefit of having well-founded neighbourhood structures is beyond their use in our local search strategy, since this allows us to incorporate them to any search method based on neighbourhoods or, if connectivity holds, they could also be used, for instance, as a branching scheme in an exact search method. Finally, although the use of heuristic strategies to generate the initial population is less frequent in the literature, there are also authors that have proved its efficacy in *fJSP* [15].

We shall propose an efficient hybrid algorithm which combines a memetic algorithm with a heuristic strategy to generate initial solutions. The initialisation strategy exploits the flexibility on the machine assignment to build a varied set of high-quality solutions. The memetic algorithm itself combines a genetic algorithm with tabu search, inspired in the method presented in [14] to solve the flexible job-shop scheduling problem with setup times. The tabu search relies on exploring both moves in machine assignments and in processing orders of critical operations. We propose two new neighbourhood structures for the local search. For the first structure, we shall prove that it verifies both feasibility and connectivity properties, the latter ensuring asymptotic convergence in probability to a global optimal solution. The second neighbourhood is obtained by incorporating a filtering mechanism that trims the first structure by discarding non-improving neighbours, keeping feasibility and considerably reducing the size of the set of neighbours at the cost of losing connectivity. Additionally, a method based on constraint propagation is introduced that allows us to speed-up the evaluation of new chromosomes. An extensive computational study will show that our algorithm outperforms existing methods from the literature for the same problem, while it gives results comparable to those of the best available algorithms for the flexible job shop with deterministic processing times.

The remainder of this paper is organised as follows: Section 2 reviews the literature on job-shop scheduling with flexibility and with uncertainty in operation processing times. Section 3 is devoted to the problem formulation while Section 4 describes the proposed algorithm, including formal proofs of the properties of the neighbourhood structure. In Section 5, we report and analyse the results of the experimental study. Finally, in Section 6, some conclusions are given.

2. Related work

Hybrid metaheuristics are classical methods for solving combinatorial optimisation problems due to the fact that they allow algorithm designers to combine different search techniques and benefit from their synergy. In particular, they have a long track of success with scheduling problems. Even for the classical *JSP*, researchers continually propose new algorithms designed from different metaheuristics which outperform or at least are comparable to previous ones. Indeed, the algorithms proposed in [16,17] are probably the most efficient approaches to the *JSP* with makespan minimisation and both combine the *i*-TSAB algorithm from [18] with other existing methods: a simulated annealing algorithm in the first case and the solution-guided search method in the second. More recently, a hybrid genetic tabu search "with innovative initial solutions" is proposed in [19] which not only solves several benchmark problems optimally but also demonstrates to be capable of solving real-life job shop problems.

Regarding the *FJSP*, several metaheuristics have been proposed since the 1990s, starting with the simulated annealing method from [20]. In [21], the authors develop a GA to maximise several objectives in a fuzzy decision making framework. This GA is later improved in [22] using random keys. In [23], a particle swarm optimisation algorithm is combined with some genetic operators. In [24], a GA that searches in the so-called space of possibly active schedules is proposed and a semantics for fuzzy schedules is provided. In [13], we find a hybrid algorithm which combines a GA with a very efficient local search method. More recently, we find a great variety of nature-inspired methods for makespan minimisation: a swarm based neighbourhood search algorithm [25], a hybrid algorithm, combining particle swarm optimisation with tabu search [26] and an artificial bee colony algorithm [27].

It is also in the 1990s that flexibility in *JSP* was first addressed by researchers, after the seminal paper [28], and has ever since been the object of intensive research. From the first works, such as [29], where the machine assignment and the scheduling of operations are studied separately, until now, many are the approaches proposed for the *fJSP*. Among others, a tabu search algorithm is proposed in [30] and is later improved with two neighbourhood structures in [31]. Ref. [15] presents a GA that incorporates different strategies for generating the initial population while a hybrid genetic algorithm combined with a variable neighbourhood descent search is given in [11]. More recently, approaches such as the discrepancy search proposed in [32], the hybrid harmony search and large neighbourhood search from [33] or the genetic algorithm combined with tabu search from [14] obtain the best results so far for many problem instances.