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A hybrid harmony search algorithm with efficient job sequence scheme and variable neighborhood search for the permutation flow shop scheduling problems

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ABSTRACT

The permutation flow shop scheduling problem (PFSSP), one of the most widely studied production scheduling problems, is a typical NP-hard combinatorial optimization problem. In this paper, a hybrid harmony search algorithm with efficient job sequence mapping scheme and variable neighborhood search (VNS), named HHS, is proposed to solve the PFFSP with the objective to minimize the makespan. First of all, to extend the HHS algorithm to solve the PFSSP effectively, an efficient smallest order value (SOV) rule based on random key is introduced to convert continuous harmony vector into a discrete job permutation after fully investigating the effect of different job sequence mapping schemes. Secondly, an effective initialization scheme, which is based on NEH heuristic mechanism combining with chaotic sequence, is employed with the aim of improving the solution's quality of the initial harmony memory (HM). Thirdly, an opposition-based learning technique in the selection process and the best harmony (best individual) in the pitch adjustment process are made full use of to accelerate convergence performances and improve solution accuracy. Meanwhile, the parameter sensitivity is studied to investigate the properties of HHS, and the recommended values of parameters adopted in HHS are presented. Finally, by making use of a novel variable neighborhood search, the efficient insert and swap structures are incorporated into the HHS to adequately emphasize local exploitation ability. Experimental simulations and comparisons on both continuous and combinatorial benchmark problems demonstrate that the HHS algorithm outperforms the standard HS algorithm and other recently proposed efficient algorithms in terms of solution quality and stability.

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1. Introduction

The production scheduling problem is a decision-making process which plays a crucial role in the manufacturing system, and widely exists in the real-world engineering fields (Pinedo, 2012). The permutation flow shop scheduling problem (PFSSP, all the expansions for the abbreviations using in this paper are listed in Table 19 in "Appendix A"), as one of the classical flow shop scheduling problems (FSSP), can be regarded as a simplified version of FSSP. The PFSSP, with the objective of minimizing the maximum completion time (namely makespan), is well-studied and has received an enormous amount of attention. As for the computational complexity, it has been proved that PFSSP with more than two machines is NP-hard (Blazewicz et al., 1983; Rand, 1977). Therefore, it is of significance both in theory and engineering applications to develop effective and efficient approaches for PFSSP.

The PFSSP was first researched by Johnson (Johnson, 1954) on the two machines, and since then a large amount of optimization approaches have been proposed for solving the PFSSP with criterion of minimizing makespan. Due to the complexity of PFSSP, many efforts have been devoted to searching for high-quality solutions in an acceptable computational time. Approaches for PFSSP can be classified into two categories: exact algorithms and heuristic algorithms. For the exact algorithms, such as branch-and-bound method, dynamical programming

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and linear programming can be only applied in solving the instances with small sizes (Della Croce et al., 1996; Ignall and Schrage, 1965; Stafford, 1988). However, for the large-scale instances, the results obtained by exact algorithms in terms of the solution quality in a reasonable time are not satisfactory. Therefore, the heuristic algorithms have been proposed.

Heuristics can be divided into three categories: constructive heuristic algorithms, improvement heuristic algorithms and hybrid heuristic algorithms. The constructive algorithms (Nawaz et al., 1983; Rajendran, 1993) are simple and fast. It can build a feasible scheduling solution through the constructive operations and usually nearly optimal solutions can be acquired in an acceptable time, while the solutions in terms of the quality are not ideal. For the improvement heuristic algorithms, most of them are the meta-heuristics. Classical meta-heuristics include Genetic algorithm (Reeves, 1995), Particle swarm optimization algorithm (Eberhart and Kennedy, 1995; Liu et al., 2007; Zhao et al., 2014b), Shuffled complex evolution algorithm (Zhao et al., 2014c, 2015c), Tabu search algorithm (Grabowski and Wodecki, 2004; Nowicki and Smutnicki, 1996), Simulated annealing (Laha and Chakraborty, 2010; Osman and Potts, 1989), VNS (Hansen and Mladenović, 2001; Moslehi and Khorasanian, 2014), Differential evolution algorithm (Li and Yin, 2013b; Storn and Price, 1997), Estimation of distribution algorithm (Wang et al., 2013; Zhao et al., 2015b), Bacterial foraging algorithm (Zhao et al., 2014a), Iterated greedy algorithm (Ruiz and Stützle, 2007) and Cuckoo search algorithm (Li and Yin, 2013a). More pleasing solutions can be obtained by using the improvement heuristic algorithm, but the evolutionary process is often time-consuming.

It is clear that a single meta-heuristic algorithm for the PFSSP has many limitations. Therefore, in order to improve the performance of the meta-heuristic, combination of two or more meta-heuristics, namely hybridization has become a hot topic and attracted much attention. The idea of hybridization is drawing strong points of the other meta-heuristics to offset itself weakness. This kind of hybridization can generate a pleasing solution in a reasonable computational time especially for large-scale instance.

In the past decades, researchers focus on the hybridization to find high-quality solutions in a reasonable time and a lot of approaches for PFSSP have been proposed. To find the minimum makespan of permutation flow shop sequencing problem, a genetic algorithm was developed by Reeves (1995). Zheng and Wang (2003) proposed an effective heuristic for flow shop scheduling. In the proposed algorithm, the NEH heuristic was employed for the population initialization and a metropolis sample of simulated annealing with probabilistic jump was incorporated into GA to strengthen the ability of local search. To solve the sequence-independent permutation flow-shop scheduling problem, a novel hybrid genetic algorithm (HGA) was introduced by Mirabi (2014). The proposed HGA made use of a modified methodology to initialize the population and an iterative swap heuristic was utilized to improve them. By utilizing the smallest position value (SPV) which is used to convert continuous vector into a discrete job permutation, A PSO algorithm for the PFSSP with objectives of minimizing makespan and total flow time criterions, namely PSOVNS, was proposed by Tasgetiren et al. (2007). The effective heuristic called variable neighborhood search (VNS) was used as local search to further enhance the ability of obtaining global solutions. Based on the memetic algorithm, an effective PSO algorithm (PSOMA) for PFSSP was developed by Liu et al. (2007), which used a simulated annealing based local search with several different neighborhood operators to balance the exploration and exploitation. Zhang and Sun (2009) applied PSO algorithm to solve the PFSSP with makespan criterion by using an alternate two phases. In the proposed algorithm, two evolutionary processes were executed alternatively to speed up the convergence performance. Based on a tabu search method with specific neighborhood definitions, a fast algorithm for the problem of finding the minimizing makespan in the PFSSP was presented by Nowicki and Smutnicki (1996), where the block of jobs was introduced. In (Gao et al., 2013), a new tabu search algorithm that combined an enhanced local search for solving the distributed permutation flow shop scheduling problem was exploited. In order to obtain the stable performance, two simulated annealing algorithm with a modified generation mechanisms were presented by Ishibuchi et al. (1995). Liu proposed a hybrid variable neighborhood search (HVNS) combining with the simulated annealing algorithm to solve the limited-buffer permutation flow shop scheduling problem with objective of minimizing makspan. Qian et al. (2008) presented a hybrid differential evolution algorithm for the single-objective PFSSP, called HDE, which designed a simple but efficient local search according to the landscape of PFSSP to reinforce the exploitation. Liu et al. (2014) applied a hybrid DE algorithm to deal with the PFSSP, which combined the individual improving scheme (IIS) and Greedy-based local search to enhance the solution quality. A hybrid cuckoo search (HCS) algorithm with objectives of minimizing makespan and total flow time for solving PFSSP was developed by Li and Yin (2013a). In the HCS, VNS algorithm with a certain probability was adopted to emphasize exploitation. In brief, different kinds of hybridizations (Dong et al., 2015; Liu et al., 2011; Xie et al., 2014) emerge in endlessly. Literatures (Baskar, 2015; Pan and Ruiz, 2013; Ruiz and Maroto, 2005) make a detailed survey about the PFSSP issue with different hybridized heuristics, which are good references.

Harmony search (HS) algorithm, as a new meta-heuristic, was proposed by Geem et al. (2001), which is one of the effective approaches for addressing combinational optimization problems. The basic idea of HS algorithm comes from the music improvisation, and mimics the process that musicians repeatedly adjust the pitches of different instruments to reach a pleasing harmony eventually. Compared with the earlier meta-heuristics, HS algorithm has many advantages such as simple concept, few parameters to be tuned and easy to be implemented, and also owns a particular behavior of exploring and exploiting the search space, which has made it quite successful in the real world (Del Ser et al., 2012; Geem, 2007; Geem et al., 2005; Xiang et al., 2014; Zhao et al., 2015a). Therefore, HS is selected as the main algorithm in this paper. For the scheduling problems, many approaches based on HS have been proposed. A chaotic harmony search (CHS) was presented by Pan et al. (2011b) to minimize the makespan for PFSSP with limited buffers. In the CHS, NEH heuristic was employed for the population initialization and a chaotic local search with probabilistic jumping scheme was designed to adequately perform exploitation. Wang et al. (2010) applied the hybrid harmony search algorithm to solve the flow shop with blocking. In order to deal with the no-wait flow shop scheduling problem with makespan criterion, a discrete HS algorithm was proposed by Gao et al. (2011). Pan et al. (2011a) proposed a local-best harmony search algorithm to handle lot-streaming flow shop scheduling problem with objectives to minimize the total weighted earliness and tardiness penalties. Yuan et al. (2013) developed a hybrid HS algorithm for the flexible job shop scheduling problem (FJSP) with the criterion to minimize makespan, and in the proposed algorithm, an improved neighborhood structure based on the critical path was adopted to speed up the local search. In Gao et al. (2014), an effective discrete harmony search (DHS) algorithm to solve flexible job shop scheduling problem (FJSP) with multiple objectives was proposed, which adopted several local search methodologies to local exploitation capability. Li et al. (2015) presented a hybrid HS algorithm to solve the multi-objective flow line manufacturing cell scheduling problem, which adopted crossover operator for diversification and employed iterative local search to further improve the solution quality.

However, from the aforementioned introduction for HS algorithm, the research on the HS for sequencing problem is still considerably limited because of its continuous nature. In this paper, a hybrid harmony search algorithm with efficient job sequence scheme and variable neighborhood search (VNS), named HHS, is proposed to solve the PFSSP with the objective to minimize the makespan. To make HHS algorithm suitable for solving PFSSP effectively, an efficient smallest order value (SOV) rule is introduced to address the conversion problem between the continuous harmony vector and the job permutation. Meanwhile, NEH

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