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A discrete Water Wave Optimization algorithm for no-wait flow shop scheduling problem

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ABSTRACT

In this paper, a discrete Water Wave Optimization algorithm (DWWO) is proposed to solve the no-wait flowshop scheduling problem (NWFSP) with respect to the makespan criterion. Inspired by the shallow water wave theory, the original Water Wave Optimization (WWO) is constructed for global optimization problems with propagation, refraction and breaking operators. The operators to adapt to the combinatorial optimization problems are redefined. A dynamic iterated greedy algorithm with a changing removing size is employed as the propagation operator to enhance the exploration ability. In refraction operator, a crossover strategy is employed by DWWO to avoid the algorithm falling into local optima. To improve the exploitation ability of local search, an insertion-based local search scheme which is utilized as breaking operator, is applied to search for a better solution around the current optimal solution. A ruling out inferior solution operator is also introduced to improve the convergence speed. The global convergence performance of the DWWO is analyzed with the Markov model. In addition, the computational results based on well-known benchmarks and statistical performance comparisons are presented. Experimental results demonstrate the effectiveness and efficiency of the proposed DWWO algorithm for solving NWFSP.
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1. Introduction

Shop scheduling is an indispensable process in manufacturing plant to provide schedule planning to produce a job sequence of the product to improve productivity for the company. Shop scheduling can be classified into Single machine scheduling with single processor, Single machine scheduling problem with parallel processors (machines), Flow shop scheduling, Job shop scheduling (Zhao, Zhang, Zhang, & Wang, 2015), Open shop scheduling (Huang & Lin, 2011) and Batch scheduling (Potts & Kovalyov, 2000). Flowshop scheduling problem (FSP) is a very active research area and has been extensively studied since it was proposed by Johnson (1954). In the last decade, FSP is also a hot issue in academic research. With the introduction of the concept of industrial Internet, the processing of products in the traditional manufacturing industry has become more complex. As a result, a variety of complex flow shop scheduling models have emerged, such as non-smooth FSP (Ferrer, Guimarans, Ramalhinho, & Juan, 2016), non-permutation FSP (Mehravaran & Logendran, 2013), mixed-blocking FSP (Riahi, Khorramizadeh, Newton, & Sattar, 2017) and hybrid-stage-shop-scheduling (Rossi, Soldani, & Lanzetta, 2015). FSP has been extended to many branches: permutation FSP (PFSP) (Shao & Pi, 2016; Zhao, Zhang, Wang, & Zhang, 2015), no-wait FSP (NWFSP), blocking FSP (BFSP) (Fernandez-Viagas, Leisten, & Framinan, 2016), no-idle FSP (NIFSP) (Shao, Pi, & Shao, 2017), flexible Flow Shop (Shahvari, Salmasi, Logendran, & Abbasi, 2012), FSP with buffers (Zhao, Tang, Wang, & Jonrinaldi, 2014) and hybrid FSP (HFSP) (Bozorgirad & Logendran, 2013; Shahvari & Logendran, 2016), etc.

The NWFSP, as an extension of the FSP, assumes that each job should be processed without waiting time between consecutive machines. In other words, in order to satisfy the no-wait constraints, the starting time of a job on a certain machine may have to be postponed. The main reason for the research of NWFSP is the technology requirement in some manufacturing environment, such as in conventional industries including steel rolling (Aldowaisan & Allahverdi, 2012), food processing (Hall & Sriskandarajah, 1996), chemical industry (Rajendran, 1994) and pharmaceutical industry (Raaymakersa, 2000) and in some advanced manufacturing systems including just-in-time production systems (Shabtay, 2012), flexible manufacturing systems(Z. Wang, Xing, & Bai, 2005) and robotic cells (Agnetis, 2000). The previous research (Röck, 1984)

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has proved that the NWFSP is a NP-hard problem with minimizing the makespan when the number of machines is more than two. It is significant to try more efficient algorithms to solve the NWFSP. NWFSP with the criterion to minimize the makespan is denoted as $Fm|no\text{-}wait|C_{\max}$ (Graham, Lawler, Lenstra, & Rinnooy Kan, 1979). In recent years, various heuristics and meta-heuristics are proposed for solving NWFSP. The algorithms for solving NWFSP can be classified into three categories: basic local search, basic population-based and hybrid algorithms between local search and population-based. A brief overview of these algorithms is given below.

The basic local search algorithm can perform a depth search within a certain range in the solution space. Ding et al. (2015) proposed a tabu-mechanism improved iterated greedy algorithm (TMIIG) to solve NWFSP. A speed-up method was adopted to expedite calculation speed and a tabu-mechanism was introduced to avoid numerous repeated-searching. As a result, three neighborhood searching methods were applied to get better solutions. Ding et al. (2015) proposed a block-shifting simulated annealing (BSA) algorithm. The BSA algorithm embeds a block-shifting operator based on k-insertion moves into the algorithm framework of simulated annealing. Wang, Li, and Wang (2010) proposed a tabu search algorithm, which incorporated speed-up operations, and compared its performance with few other existing heuristics. Wang (2014) presented a fast iterated local search (FILS) algorithm with high order (polynomial size) neighborhood. In the FILS algorithm, a new neighborhood along with the insertion neighborhood is used in variable neighborhood.

Population-based algorithms have good performance in global search. Gao, Pan, and Li (2011) presented a discrete harmony search algorithm (DHS) to solve the NWFSP with the objective to minimize total flow time. A novel pitch adjustment rule is employed in the improvisation to produce a new harmony. Nagano, Silva, and Lorena (2014) proposed an Evolutionary Clustering Search algorithm which divided the search space into clusters and picked out some promising search space areas from the clusters.

Hybrid algorithm combining local search with population-based global search is a more popular optimization framework. Jarboui, Eddaly, and Siarry (2011) proposed a new crossover mechanism in GA for solving NWFSP, and the variable neighborhood search (VNS) was applied to improve the quality of solutions. Samarghandi and ElMekkawy (2012) presented a hybrid algorithm combining PSO with TS algorithm. They showed that the hybrid algorithm performs better than other hybrid PSO algorithms. Akrout, Jarboui, Rebaï, and Siarry (2013) proposed a hybrid greedy randomized adaptive search procedure (GRASP) with DE for solving NWFSP. The parameters were adjusted by using DE algorithm. Davendra, Zelinka, Senkerik, and Jasek (2011) presented a novel discrete self-organizing migrating algorithm (DSOMA) for solving NWFSP, in which the 2-OPT local search was introduced to improve the quality of solutions.

Based on the shallow water wave models, the WWO algorithm was first proposed by Zheng (2015). These models derive three effective mechanisms: propagation, refraction and breaking. The WWO algorithm framework composed of the three operators is a good way to balance the capabilities of its local search and global search. In numerical tests and practical applications, the WWO algorithm shows efficient performance. At present, the WWO algorithm and its modifications have been utilized to solve many problems, such as economic dispatch problems (Siva, Balamurugan, & Lakshminarasimman, 2016), selection of key components of software formal development (Zheng, Zhang, & Xue, 2016) and other fields. Thereafter, some attempts to employ the WWO to solve the combinatorial optimization problem have emerged. Wu, Liao, and Wang (2015) redefined the WWO algorithm to solving TSP. Yun, Feng, Xin, Wang, and Liu (2016) first applied WWO algorithm to solve the flow-shop scheduling problem.

Currently, there is no reported study on the WWO algorithm to solve the NWFSP. The contributions of this study can be summarized as follows:

- We retain the original framework of the algorithm and redefine the three operators of WWO algorithm to solve $Fm|no\text{-}wait|C_{\max}$. As a simple and efficient local search algorithm, iterated greedy (IG) algorithm (Ruizab, 2007) is introduced as the propagation operator. The crossover operator and the insert-based local search are applied as the refraction and breaking operators respectively.
- In order to improve the quality of the initial population, a modified initialization strategy which combined nearest neighbor heuristic (NN) (Fink & Voß, 2003) with MNEH (Gao et al., 2011) algorithm is proposed. A ruling out inferior solution operator is introduced into the framework of WWO to enhance the convergence capability.
- At the same time, the convergence performance of the DWWO algorithm is analyzed. The convergence process of the candidate solution is mapped to the state transition process in the Markov chain and the convergence performance of the algorithm is proved.

The remainder of the paper is organized as follows: Section 2 gives the problem formulation on $Fm|no\text{-}wait|C_{\max}$. Section 3 provides a brief introduction of the original WWO algorithm. In Section 4, the proposed DWWO algorithm is described in detail for $Fm|no\text{-}wait|C_{\max}$. Section 5 makes a global convergence analysis of DWWO based on the Markov Chains. In Section 6, the main parameters are set. Then several experiments are given to verify the performance of the proposed algorithm. Section 7 summarizes conclusions and future work.

Some symbols used mostly through this paper are summarized as follows:

n	number of jobs
m	number of machines
π	the sequence of all jobs
π_i	the ith sequence (or individual) in population
$\pi(i)$	the ith job in sequence π
$\pi_i(j)$	the jth job in the ith sequence
$C_{max}(\pi)$	the make span of π
$p(\pi(i),k)$	the processing time for the $\pi(i)$ on the kth machine
$D(\pi(i\text{-}1), \pi(i))$	the processing delay time between job $\pi(i\text{-}1)$ and job $\pi(i)$
NP	the population size
λ	the wave length
λ_i	the wave length of the ith sequence
h	the wave height
h_i	the wave height of the ith sequence
α	the coefficient of ruling out inferior solution
π_D	sub-sequence containing d jobs
π_R	sub-sequence containing $(n\text{-}d)$ jobs
Π	the set of all possible permutations

2. No-wait flow shop scheduling problem(NWFSP)

NWFSP can be described as follows: n jobs are processed on m machines, and the processing routes of all jobs on m machines are the same. Several restrictions are set: A job can be only processed on a single machine at a certain moment; a machine can only process a job at a time; each job must be processed without waiting time between consecutive machines. The processing time of each job on each machine is given before. The target of scheduling is to find the best sequence which has the minimum makespan. To

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