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A hybrid genetic algorithm for the hybrid flow shop scheduling problem with nighttime work and simultaneous work constraints: A case study from the transformer industry

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ABSTRACT

This paper addresses a hybrid flow shop scheduling problem with real-world constraints, and proposes a novel algorithm for its solution. We first discuss the distinguishing characteristics of nighttime and simultaneous work in the transformer manufacturing process. To solve the problem within a reasonable time, we propose a hybrid genetic algorithm. This algorithm combines the Nawaz–Enscore–Ham (NEH) heuristic, a local search algorithm, and a machine allocation rule with the aim of minimizing the total tardiness. Our experimental results show that the proposed algorithm outperforms the NEH algorithm, a simple genetic algorithm, and five existing dispatching rules in terms of average total tardiness performance and relative deviation index. The proposed algorithm is also shown to be competitive with respect to its efficiency and robustness.

1. Introduction

The flow shop scheduling problem is common in many production systems. In certain environments, parallel machines are made up of multiple copies and grouped into stages. For these production environments, the traditional flow shop scheduling model is inappropriate, because some stages utilize parallel machines. This type of problem can be defined as a hybrid flow shop scheduling problem (HFSP).

The hybrid flow shop is an extension of the production system in a traditional flow shop. It consists of two or more stages in series and one or more parallel machines at each stage to increase productivity and flexibility. Examples of hybrid flow shop problems are floor covering production, glass-bottle industry, and so on (Lopez & Roubellat, 2008).

In this type of shop, the major issues are the allocation of jobs to machines at each stage, and the sequence of jobs assigned to each machine. HFSPs have been extensively studied; however, most examples are NP-hard (Linn & Zhang, 1999).

This paper focuses on the scheduling problem in hybrid flow shops with two distinguishing constraints: the consideration of daytime and nighttime work teams and simultaneous work of specific order types. Our research is motivated by an industrial transformer manufacturing system with a number of availability conditions between various product types and machines. In this case, a feasible solution that minimizes the total tardiness (that is, the total time by which order processing is delayed) is vitally important, because the penalty cost of tardy jobs has a detrimental effect on a company.

In addition to the characteristics of the general HFSP, there are constraints on the waiting times between successive stages of a job, as well the consideration of nighttime work and simultaneous work at each stage.

This paper is organized as follows. In the next section, previous research into hybrid flow shop scheduling is reviewed. The problem and constraints of a transformer manufacturing system are defined in Section 3, and a hybrid genetic algorithm to solve this problem is then proposed in Section 4. Section 5 summarizes the results of experiments to verify our approach. Finally, our conclusions and areas for further research are discussed in Section 6.

2. Literature review

Arthanari and Ramamurthy (1971) considered the HFSP, and proposed the first Branch and Bound method. Kochhar and Morris (1987) developed heuristic algorithms to minimize the mean flow time for the flexible flow line problem with finite buffers. They divided the problem into two sub problems: entry point sequencing and dispatching. The two-stage HFSP was shown to be

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NP-hard by Gupta (1988). Gupta, Hariri, and Potts (1997) then showed that a non-preemptive two-stage HFSP is NP-hard in the strong sense.

Exact approaches based on mathematical modeling can ensure higher performance than heuristic methods in finding optimal solutions of HFSP. Fattahi, Hosseini, Jolai, and Tavakkoli-Moghaddam (2014) developed a branch-and-bound algorithm that considered the setup time and assembly operations to minimize the makespan for HFSP. Sun and Yu (2015) deal with a two-stage HFSP with batch constraints and the variable processing times through a Lagrangian relaxation approach. However, because of their NP-hard nature, exact approaches are only applicable to small-scale problems. Thus, heuristic algorithms are widely used to obtain good approximations within a reasonable time (Ribas, Leisten, & Framiñan, 2010). Examples of such heuristic algorithms are the neighborhood search, simulated annealing, and genetic algorithms (GAs).

Heuristic approaches have been devised for solving the HFSP constraints that arise in actual applications. Holland (1975) first proposed the GA concept in his book "Adaptation in Natural and Artificial Systems". In traditional GAs, mutation is used to produce small changes to chromosomes, resulting in a varied population. Unlike traditional GAs, Tsujimura and Gen (1999) proposed a mutation operator with a neighborhood search technique to determine near-optimal solutions. Botta-Genoulaz (2000) proposed a heuristic algorithm based on the earliest due date (EDD) sequencing method with First Available Machine and Last Busy Machine allocation rules for the HFSP. Engin, Ceran, and Yilmaz (2011) proposed an efficient GA for hybrid flow shop scheduling with multiprocessor tasks. Liao, Tjandradjaja, and Chung (2012) proposed a particle swarm optimization (PSO) algorithm for the HFSP with a minimum makespan objective. They developed a hybridizing PSO with a bottleneck heuristic and simulated annealing to help escape from local optima. Bożejko, Pempera, and Smutnicki (2013) designed a parallel tabu search algorithm for an HFSP derived from automated manufacturing lines. Costa, Cappadonna, and Fichera (2014) considered a GA for the HFSP with parallel batching and eligibility constraints. Li, Pan, and Wang (2014) combined a neighborhood search algorithm with both chemical-reaction optimization and an estimation of distribution to minimize the HFSP makespan. Rossi, Pandolfi, and Lanzetta (2014) developed dynamic set-up rules for HFSP with parallel batching machines. They introduced heuristics based on the critical ratio between the setup and processing times to minimize makespan and the number of tardy jobs.

There are still two issues relevant to the majority of flow shop scheduling research. The first issue is the great complexity of real-world problem sizes. Unfortunately, although exact approaches such as MILP and dynamic programming can find an optimal solution, they are often impractical because of the extremely long calculation time for large problems. On the other hand, heuristic approaches such as GAs can be applied to more complex problems. However, the execution time and solution quality vary with the design of the algorithm. Thus, there is a significant need for efficient heuristic or meta-heuristic methods.

The second issue is the determination of various constraints in industry and their consideration in an algorithm. In real-world problems, a typical flow shop with a single machine at each stage rarely exists. Generally, there will be a variety of machines with different abilities placed in parallel at stages to increase capacity and balance the workload (Naderi, Gohari, & Yazdani, 2014). Although there have been a number of previous research articles on HFSPs in manufacturing systems, the assumptions made when developing their algorithms mean they have limited applicability (Ruiz & Vázquez-Rodríguez, 2010). Thus, consideration of other constraints, such as unrelated parallel machines and eligibility, is a significant step towards increasing the possibility of application in the field, and is thus worthy of further research.

The limitations of previous research with regard to these two issues make the study of a hybrid approach to HFSP more interesting. In this paper, Section 3 broaches the second issue by presenting the distinguishing constraints in a transformer production factory. Section 4 then deals with the first issue by describing a hybrid algorithm that efficiently incorporates a GA into heuristic methods.

3. Problem definition

In consideration of increasing market competition and the need to present a range of voltages and capacities, several types of transformer should be included in the scheduling process. In addition, there are a number of parallel machines (workbenches and drying furnaces) at each stage of the process, each with their distinguishing constraints. The entire process of transformer production is summarized in Fig. 1.

The problem is to schedule a hybrid flow shop (HFS) with m stages. Each stage has several machines operating in parallel, but the flow of jobs through stages is unidirectional. Some stages may have only one machine, but at least one stage must have multiple machines. The type of parallel machines can be identical, uniform, or unrelated. An operation refers to a specific period of processing by the selected machine.

Using the well-known three-field notation (Pinedo, 2008), the transformer production problem can be denoted by $FH2,\left(\left(RM^{(k)}\right)_{k=1}^{2}\right)|r_j|\sum T_j$ (Ruiz & Vázquez-Rodríguez, 2010). The type of parallel machines is the unrelated parallel machine that the processing time depends on the allocated machine. In certain practical applications with continuous job processing, such as in the plastics industry, there is limited intermediate storage space between stages (Moradinasab, Shafaei, Rabiee, & Ramezani, 2013). In this case, the number of jobs in intermediate storage should be minimized to reduce inventory costs. This implies that the waiting queue between two successive stages operates under the FIFO principle.

The following assumptions are also considered in this paper.

1. The number of stages and number of machines at each stage are known in advance. The number of jobs and their processing times are also known in advance.
2. Each machine can process only one job at a time. Pre-emption is not allowed.
3. All the machines are available for the entire period of scheduling, and there are no machine breakdowns.
4. The objective is to minimize the total tardiness. The total tardiness is defined as:

$$\text{Total Tardiness} = \sum_{i=1}^{n} max(0, C_i - d_i)$$

where C_i is the completion time of job i, d_i is the due date of job i, and n is the number of jobs.

3.1. Distinguishing constraints

3.1.1. Nighttime work

Work teams can be divided into three subteams: two daytime teams and one nighttime team, as in Fig. 2. In a transformer production plant, a dividable work team generally has two workbenches to process their Stage 1 operations, i.e., each daytime