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Flexible job-shop scheduling with routing flexibility and separable setup times using ant colony optimisation method

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Abstract

This paper proposes an ant colony optimisation-based software system for solving FMS scheduling in a job-shop environment with routing flexibility, sequence-dependent setup and transportation time. In particular, the optimisation problem for a real environment, including parallel machines and operation lag times, has been approached by means of an effective pheromone trail coding and tailored ant colony operators for improving solution quality. The method used to tune the system parameters is also described. The algorithm has been tested by using standard benchmarks and problems, properly designed for a typical FMS layout. The effectiveness of the proposed system has been verified in comparison with alternative approaches.

Keywords: Job-shop scheduling; Ant colony optimisation; Flexible manufacturing systems

1. Introduction

A basic production planning behaviour desired in an FMS is to support routing flexibility and operation lag times. In this context, the following features are considered:

- *routing flexibility*: alternative paths can be followed through the system for a given process plan [1];
- *separable setup*: each operation is subjected to a setup; the setup period is split in the following two independent activities to be performed in parallel: (i) the setup depending on the previous processed operation on the machine (*sequence-dependent* setup); (ii) the setup depending on the previous operation in the job routing (*sequence-independent* setup) [2].

Routing flexibility leads to the problem of *flexible* (or multiprocessor) *job-shop scheduling* (FJS) which extends the classic problem of job-shop scheduling where no alternative machine is present for processing an operation [3]. The FJS problem concerns two sub-problems: (i) assignment of each operation to one of the alternative machines (*assignment sub-problem*); (ii) ordering of the operations on each assigned machine (*sequencing sub-problem*), with the aim of optimising an objective function.

In a very large number of practical industrial applications, routing flexibility is combined with the *total grouping* model of an FMS, which consists of a partition of available machines into groups of identical machine tools [1,4]. The related job-shop scheduling problem is identified by FJS with *parallel* (or replicated) *machines* (FJS-PM). Pools of identical machines are dedicated to process a quite large number of operations and, therefore, to give parallel processing capabilities to each operation in the process plan.

The routing flexibility is also used to tackle production stops, if busy or inoperative machines occur. It replaces and often outperforms the availability of alternative process plans for a given part (*operation flexibility*). Each group accomplishes a desired amount of automation, productivity and machine flexibility [5].

The possibility of using *anticipatory setups* and *overlapping* of transportation and processing times increases machine flexibility and reduces costs. An anticipatory setup allows the part to be not necessarily available on the machine during the setup period. Overlapping of transportation activities and processing times allows the part to

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move to the next machine when the previous operation on the machine is not necessarily completed. New solution techniques to tackle stops of workstations caused by waiting for material-handling system (*material-handling interference* (MHI), [6]) allow to reduce the elapsed time spent to serve parts on the next machine (i.e., *sequence-independent* setup times).

Job-shop scheduling, which only deals with the sequencing sub-problem, is strongly NP-hard [7]; only few special cases can be optimally solved with acceptable computing times. As it is an extension of job-shop scheduling, FJS with routing flexibility and separate setup is NP-hard as well, justifying the use of heuristics or approximation algorithms to approach the problem [8,9]. The majority of scheduling researches in literature assumes the setup time as negligible or a part of the processing time. While these assumptions simplify the analysis in certain applications, they adversely affect the solution quality. On the other hand, when these concepts are considered, there is a lack of investigation on FMS scheduling system that supports routing flexibility for practical industrial applications. For a very special case of job-shop scheduling, the two-machine flow-shop, separate activities of machine setup and job transportation are considered by Nabeshima and Maruyama [10] and, more recently, by Yang and Chern [11]. This problem has been generalised to *n* machines by means of a shifting bottleneck procedure by Ivens and Lambrecht in the case of flow-shop with parallel machines [12]. The knowledge is based on the *disjunctive graph* (digraph) model, which extends that one originally proposed by Roy and Sussman [13]. The disjunctive graph representation is becoming the standard model for scheduling applications. In fact, these graphs are more efficient, than Gantt diagrams, to describe the knowledge for optimisation search techniques [9]. In job-shop scheduling, some approaches with sequence-dependent setup times assume the material-handling systems as a further machine, where travelling operations involve non-negligible transportation times [14,15]. Thus, the material-handling system is considered as an additional machine type, which can be scheduled together to the other machines in order to transform the general problem into the job-shop scheduling with sequence-dependent setup times. Nevertheless, in such approaches, the scheduling algorithm works on twice the number of operations and one (or more) further machines included in the material-handling system. Ref. [16] deals with the FJS-PM where separable setup and transportation times are related to a *single operation setup* phase. This approach reduces the number of operations in the system because no additional machine is used to model transportation times. Nevertheless, in this reference, the problem knowledge for an evolutionary approach is still modelled by a Gantt diagram.

This paper describes a new methodology to support routing flexibility and separate setups. It is based on the disjunctive graph representational model of the FJS problem with separable transportation and sequence-dependent setup times. A fast algorithm with minimum computational complexity on the digraph is developed in order to build a feasible solution including the value of its objective function. Here, the aim is to minimize the makespan, although an amount of results is independent of the selected objective function. The graph representation of the problem makes possible a more direct visit by means of a promising metaheuristic search routine: ant colony optimisation (ACO, [17]). ACO is an emerging class of research, dealing with swarm intelligence, a set of artificial life methods that exploit the experience of an ant colony as a model of self-organisation in co-operative food retrieval by means of a proper pheromone trail model. In particular, the algorithm that builds a feasible solution on the digraph, is used by an artificial ant to generate its nest-food path.

2. FJS with routing flexibility and setup constraints

Formally in FJS-PM, n jobs have to be scheduled on m pools of machines each including m_j ($j = 1, \dots, m$) identical (or parallel) machines, so that the quantity $k = \min_{j=1,\dots,m} m_j$ represents the degree of *parallelization* capability of the system. The problem with equal-size pools, i.e. $m_j = k$ for each pool j, is also referred as the FJS-kPM *problem*. Each job i must be processed in accordance with its *linear routing* represented by a sequence of $l_i \leqslant m$ operations, O_{ijr}, each of these has to be processed as the rth operation on a single machine among that ones belonging to the jth pool, with a processing time t_{ijr} and a setup activity f_{ij}, which takes the time $t(f_{i,j})$; $st(O_{ijr})$ and $t(O_{ijr})$ denote, respectively the starting and the completion time of the operation. No machine can process more than one operation at a time; no operation O_{ijr} can start until $O_{ij',r-1}$ is completed or can stop after it starts; finally, an operation must be processed by one, and only one, machine. In order to process the entire set of planned operations, the system includes F dedicated setup activities, grouped per pool of machines, $F_1, \dots, F_m$. A machine of the pool j includes all the machine equipment capable of performing the setup activity f_{ij} of the set F_j (i.e. no sharing of tools, jigs, fixtures, etc. is allowed among machines). Each job i and each machine h are subjected to a release date, D_i and d_h, respectively. Finally, a material-handling system is able to offer the required flexibility in order to move a part through the system. A transportation time matrix δ includes the times to move a job among the stations; t_A is the instant of availability of the material-handling system.

Job-shop scheduling is a particular case of FJS-PM where the number of machines in each pool is $m_j = 1$. The assignment of operations to a machine of a pool gives a sort of further flexibility, and hence an increase of complexity, in addition to the flexibility represented by the possibility of sequencing operations on the machines. In opposite to the classic problem, the FJS has been only treated in the recent literature (see for example [2,18–20]). Although a number of flexible job-shop methods could