Computers & Industrial Engineering 91 (2016) 290–301

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Minimizing the total completion time on a parallel machine system with tool changes

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ARTICLE INFO

Article history:
Received 5 August 2015
Received in revised form 10 November 2015
Accepted 21 November 2015
Available online 5 December 2015

Keywords:
Tool change
Unavailability
Metaheuristics
Mixed integer linear programming
Dunn's test

ABSTRACT

In this paper, the identical parallel machine scheduling problem with periodic tool changes due to wear is addressed under the total completion time minimization objective. Due to machine availability restrictions induced by tool replacement operations, the problem is *NP*-hard in the strong sense. A mixed integer linear programming (MILP) model has been developed with the aim to provide the global optimum for small-sized test cases. Furthermore, a hybrid metaheuristic procedure based on genetic algorithms has been specifically designed to cope with larger instances. A comprehensive experimental analysis supported by a non-parametric statistical test has been fulfilled to select the best metaheuristic configuration in terms of decoding strategy and parameters driving the search mechanism as well. Then, the proposed optimization procedure has been compared with three alternative methods arising from the relevant literature on the basis of a wide benchmark of test cases. The obtained results, also supported by a proper statistical analysis, demonstrate the effectiveness of the proposed approach for solving the tool change scheduling problem at hand.

1. Introduction

The body of literature focusing on scheduling assumes that machines are continuously available along the planning horizon. Actually, in many real industry situations, machines may temporarily be out of service due to failures, maintenance activities or shift changes (Framinan, Leisten, & Ruiz García, 2014). When the machine availability restriction follows a certain probability distribution the scheduling problem is denoted as stochastic. However, the deterministic issue according to which unavailability intervals are known in advance, continues to gain a great approval by literature, as confirmed by three well-known surveys proposed by Lee, Lei, and Pinedo (1997), Schmidt (2000) and Ma, Chu, and Zuo (2010), respectively.

Up to date, most of literature focused on deterministic issues involving just a single unavailability interval per machine throughout the whole planning horizon. Accordingly to Chen (2006), the starting time of this interval may be constant and a priori known (*Problem SC*) or it may be a decision variable (*Problem SV*). Such scheduling issues have been extensively investigated so far, with reference to single machine (Adiri, Bruno, Frostig, & Rinnooy Kan, 1989; Breit, 2007; Lee & Liman, 1992; Sadfi, Penz, Rapine, Błażewicz, & Formanowicz, 2005), parallel machine (Lee, 1996; Lee & Liman, 1993; Mosheiov, 1994), flow shop (Allaoui, Artiba, Elmaghraby, & Riane, 2006; Lee, 1997) and job shop (Aggoune, 2002; Zribi & Borne, 2005) production systems.

On the other hand, periodic availability restrictions (e.g. due to regular maintenance activities on machines) motivated the study of scheduling problems affected by multiple unavailability intervals whose starting times may be constant (*Problem MC*) or a decision variable (*Problem MV*). Similarly, Sbihi and Varnier (2008) observed the same issues under the maintenance viewpoint, thus distinguishing between periodic maintenance (PM) and flexible periodic maintenance (FPM).

As regards the *Problem MC* related topic, most research is relegated to single machine production systems Liao and Chen (2003), Ji, He, and Cheng (2007), and Chen (2007), while Gholizadeh, Tavakkoli-Moghaddam, and Tootooni (2012) and Allaoui and Artiba (2004) applied different metaheuristic algorithms, namely genetic algorithm and simulated annealing, to a flowshop production system where several unavailability intervals are required for each workstation.

As far as the *Problem MV* is concerned, Qi, Chen, and Tu (1999) and Graves and Lee (1999), proved that the total completion time minimization problem on a single machine is *NP*-hard in the strong sense, for non-resumable and semi-resumable jobs, respectively.

More recently, several contributions concerning with the preventive maintenance topic in a flowshop environment have been

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http://dx.doi.org/10.1016/j.cie.2015.11.015
0360-8352/

proposed. Ruiz, García-Díaz, and Maroto (2007) proved the significance of taking into consideration preventive maintenance together with sequencing and the consequences of not doing so. On the basis of those findings, Jabbarizadeh, Zandieh, and Talebi (2009), Naderi, Zandieh, and Fatemi Ghomi (2009), and Naderi, Zandieh, and Aminnayeri (2011), proposed a simulated annealing, a variable neighborhood search (VNS) and an artificial immune system (AIS) algorithm, respectively, to solve the makespan minimization problem in flexible flowshop production systems under different maintenance strategies, also including the FPM policy.

Besides maintenance tasks, the tool replacement issue can be considered as another source of restrictions in terms of machine availability. Machine unavailability arising from tool changes may affect the performance of several real-world manufacturing processes like metal or wood cutting (Yang, Cheng, Yang, & Hsu, 2012, Zarook and Abedi, 2014), integrated circuit (IC) testing operations and printed circuit board (PCB) production (Low, Ji, Hsu, & Su, 2010) and machining operation in manufacturing cells (Alfieri & Nicosia, 2014). Tool changes may be motivated by part mix production (Hertz, Laporte, Mittaz, & Stecke, 1998; Tang & Denardo, 1988), though those due to wear are approximately 10 times more frequent, as observed by Gray, Seidmann, and Stecke (1993). In a tool-change scheduling problem with wear effects, tools must be replaced before they reach the end of their service life. In words, the maximum allowed working time between two consecutive tool changes may be denoted by Δ, being Δ the provided tool life. As a result, such problem may be formally configured as a *Problem MV* as well as a FPM issue.

The single-machine tool-change scheduling problem attracted most of academics and practitioners, so far. Akturk, Ghosh, and Gunes (2004) discussed the computational complexity of such issue, also providing a worst-case lower bound for the SPT heuristic. Three years later, Akturk, Ghosh, and Kayan (2007) analyzed the effect of tool changes and controllable machining conditions on a CNC workstation under the total completion time minimization objective. The authors proposed a mixed integer linear programming (MILP) formulation able to solve up to 30-job problems, and a problem space genetic algorithm to tackle large-sized instances. Chen (2008) compared two alternative MILP models for the total tardiness minimization problem. Recently, Xu, Liu, Yin, and Hao (2013) investigated a different single machine tool change scheduling problem where a set of special jobs has to be processed within the first portion of tool life. In order to minimize the makespan, the authors proposed two MILP models and six heuristic algorithms to be employed for small- and large-sized instances, respectively.

To the best of our knowledge, the tool change scheduling issue on parallel machines has not been investigated by literature so far. On the other hand, availability restrictions related to multiple stages production systems as well as parallel machines received a small consideration by literature so far and a relatively few papers exists. Lee and Chen (2000) studied the problem of jointly scheduling jobs and maintenance activities on a set of identical parallel machines that must be maintained exactly once with a constant maintenance length (i.e. Problem MC). Xu, Sun, and Li (2008) approached the parallel machine scheduling problem with almost periodic maintenance activities under the makespan minimization viewpoint. In particular, they proved the *NP*-hard complexity of the problem at hand and proposed a polynomial time-approximation algorithm named BFD-LPT to solve that. Recently, Yang et al. (2012) and Zarook and Abedi (2014) investigated the unrelated parallel-machine environment with aging effect and multi-maintenance activities. Indeed, both of them consider that jobs processing times increase due to wear effect; thus, a machine reverts to its initial condition after maintenance and the aging effects start anew. The former research group proved that the problem pertaining to the total machine load minimization can be polynomially solved when their maintenance frequencies on the machines are given. The latter implemented a genetic algorithm based on a matrix encoding such that the total early/tardy and maintenance cost be minimized.

The present paper addresses the problem of scheduling n jobs on m parallel machines subjected to tool change operations induced by tool wear. Differently from the aforementioned papers focused on parallel machines with aging effects and maintenance activities, in the problem under investigation the time required for processing a product does not depend on the quality of the tool. Therefore, the tool must be replaced once its provided service life is achieved. The problem under investigation may be observed in many real life situations. For instance, it may concern with a set of parallel Computer Numerical Control (CNC) machines with only one type of tool with a known, constant life and unlimited availability. (The use of one tool type is not unusual in practice as illustrated by the case of CNC drills). Alternatively, wood, stone or metal cutting may be considered as a further real-life application.

The objective to be minimized is the total completion time. Firstly, a mixed integer linear programming model has been devised with the aim of optimally solving small- to medium-sized instances. Then, in order to tackle larger problems, typical of real-world industrial situations, a hybrid optimization procedure integrating features from genetic algorithms and local search methods has been developed. The effectiveness of the proposed metaheuristcs has been validated through a comprehensive comparison analysis involving three alternative metaheuristic algorithms proposed by the relevant literature and properly adapted to the problem at hand. The objective of this paper is proposing a MILP model and a novel efficient hybrid metaheuristics to solve both small- and large-sized instances concerning with the parallel machine tool change scheduling issue.

The remainder of the paper is organized as follows. In Section 2 the problem statement is outlined. Section 3 reports the MILP formulation. Details of the proposed hybrid metaheuristic procedure are provided in Section 4. Section 5 describes the calibration campaign executed to properly tune the algorithm. In Section 6, the alternative methods adapted from the literature are presented. Outcomes from an extensive numerical analysis aiming to assess the performances of the proposed metaheuristic algorithms are presented in Section 7. Finally, Section 8 concludes the paper.

2. Problem description

The proposed parallel machine tool change scheduling problem can be stated as follows. A set of n ($j = 1, 2, \ldots, n$) independent jobs has to be worked in a manufacturing stage made by $m(i = 1, 2, \ldots, m)$ identical parallel machines. Each job must be processed by only one machine, and machines cannot process more than one job at a time. Each machine makes use of a tool to process jobs. Each tool is subject to wear and has a finite service life, denoted as *TL;* thus, it must be replaced by a new tool before its service time reaches *TL* time units. Every tool change task entails a machine unavailability interval equal to *TC*. The stock of new tools is supposed to be unlimited. Preemption is not allowed, i.e., job processing cannot be interrupted because of tool changes. At time zero all machines are supposed to be available and equipped with newly-installed tools. All jobs are ready to be processed at time zero. The objective function to be minimized is the total completion time.

Qi et al. (1999) proved that minimizing the total completion time for a single machine subjected to regular shutdowns after a certain amount of working time is *NP*-hard in the strong sense. Since the scheduling problem here investigated entails m parallel machines, where $m \geqslant 1$, it can be argued that it is *NP*-hard in the strong sense, as well.