Computers & Industrial Engineering 83 (2015) 226–236

Contents lists available at ScienceDirect

Computers & Industrial Engineering

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

An integrated three-stage maintenance scheduling model for unrelated parallel machines with aging effect and multi-maintenance activities ☆

Madjid Tavana [a,b,*], Yaser Zarook [c], Francisco J. Santos-Arteaga [d]

[a] Business Systems and Analytics Department, Lindback Distinguished Chair of Information Systems and Decision Sciences, La Salle University, Philadelphia, PA 19141, United States
[b] Business Information Systems Department, Faculty of Business Administration and Economics, University of Paderborn, D-33098 Paderborn, Germany
[c] Department of Industrial Engineering, Mazandaran University of Science and Technology, Babol, Iran
[d] Departamento de Economía Aplicada II, Facultad de Económicas, Universidad Complutense de Madrid, Campus de Somosaguas, 28223 Pozuelo, Spain

ARTICLE INFO

Article history:
Received 19 April 2014
Received in revised form 7 January 2015
Accepted 11 February 2015
Available online 2 March 2015

Keywords:
Maintenance scheduling
Unrelated parallel machines
Fuzzy sets
AHP
TOPSIS
Goal programming

ABSTRACT

We propose an integrated three-stage model for maintenance scheduling of unrelated parallel machines (UPMs) with aging effect and multi-maintenance activities (AEMMAs) using a variety of MODM techniques such as the fuzzy analytic hierarchy process (AHP), the technique for order of preference by similarity to ideal solution (TOPSIS), and goal programming (GP). We use fuzzy AHP in the first stage of the proposed model to account for the inherent ambiguity and vagueness in real-life maintenance scheduling problems. In the second stage, we use TOPSIS to reduce the multi-objective problem into an efficient bi-objective problem. Finally, we use GP to solve the resulting bi-objective problem and develop an optimal maintenance schedule in the third stage of the model. We use a numerical example to demonstrate the applicability of the proposed approach and exhibit the efficacy of the procedures and algorithms.

1. Introduction

Manufacturing firms are constantly under pressure to reduce their production costs. Maintenance costs, one of the main components of production costs, substantially add to this stress in the manufacturing environment (Bevilacqua & Braglia, 2000). Although manufacturing firms constantly seek to engage all levels and functions in an organization to maximize the overall effectiveness of production equipment, maintenance costs are unavoidable and play an important role in maintaining a machine's reliability and product quality. Although manufacturers have made great strides in controlling maintenance cost, maintenance remains an important topic for further study in production economics and research.

In deterministic scheduling problems, the job processing time is assumed constant and independent of its position or starting time in the scheduling process. However, there are many situations in which the actual processing times of the jobs may vary due to learning, aging or deterioration effects (readers should refer to Biskup (2008), Janiak & Rudek (2006) and Janiak & Rudek (2009) for the state of the current research). The motivation for this study stems from the metal or wood cutting process that cuts products to various sizes and shapes them in a parallel-machine setting. Due to wearing of the cutting tool, the actual processing time of the product increases with respect to the number of products already processed on the machine. The time required for processing a product depends on the quality of the cutting tool. Therefore, under normal circumstances, the cutting tool is replaced with a new one or is maintained after it has processed some products to improve its production efficiency.

Maintenance activities in the literature have been classified into two main categories: corrective and preventive (Li, Khoo, & Tor, 2006; Waeyenbergh & Pintelon, 2004). The corrective maintenance is the maintenance that occurs after systems failure (Swanson, 2001) while the preventive maintenance is the maintenance that is performed before systems failure in order to retain equipment in specified condition by providing systematic inspections, detection, and prevention of incipient failure (Moghaddam, 2013; Wang, 2002). The model proposed in this study falls in the preventive maintenance category.

One of the first steps of maintenance activities is to select the best repairmen from a pool of available repairmen. In this paper,

☆ This manuscript was processed by Area Editor T.C. Edwin Cheng.

* Corresponding author at: Business Systems and Analytics Department, Lindback Distinguished Chair of Information Systems and Decision Sciences, La Salle University, Philadelphia, PA 19141, United States. Tel.: +1 215 951 1129; fax: +1 267 295 2854.

E-mail addresses: tavana@lasalle.edu (M. Tavana), yacerzarok@yahoo.com (Y. Zarook), fransant@ucm.es (F.J. Santos-Arteaga).

URL: http://tavana.us/ (M. Tavana).

http://dx.doi.org/10.1016/j.cie.2015.02.012

the analytic hierarchy process (AHP) is used to select the most suitable repairmen based on a set of pre-specified evaluation criteria (Saaty, 1980). AHP can consider both quantitative and qualitative evaluation criteria. Most qualitative evaluation criteria in real-life are often accompanied by ambiguities and vagueness. Therefore, we consider fuzzy logic and fuzzy sets to represent ambiguous and vague information in the evaluation process. The integration of AHP and fuzzy set theory (Bellman & Zadeh, 1970) has resulted in the fuzzy AHP method.

Parallel machine scheduling (PMS) is concerned with the allocation of a set of jobs to a number of parallel machines. The studies on PMS in the literature have been generally categorized into three groups: identical, uniform and unrelated PMS problem (Cheng & Sin, 1990). Among these groups, unrelated PMS (UPMS) represents a generalization of the other two groups where different machines perform the same job but have different processing capacities or capabilities. However, solving real-life UPMS problems is a difficult task because they are mostly NP-hard (Torabi, Sahebjamnia, Mansouri, & Aramon Bajestani, 2013). This paper focuses on the UPMS problems, which have been addressed much less than the identical and uniform PMS problems in the literature (see Arnaout, Rabadi, & Musa, 2010; Chang & Chen, 2011).

In spite of huge advances in PMS research, multi-objective scheduling problems with simultaneous consideration of repairmen selection, aging effects and maintenance activities under unrelated parallel machine environment have not been thoroughly studied in the literature. Kuo and Yang (2008) studied single-machine scheduling problems with a cyclic process of aging effects and multi-maintenance activities. They investigated the problem with job-independent and position-dependent aging effects to minimize the makespan. Zhao and Tang (2010) extended the study of Kuo and Yang (2008) to the case with a job-dependent aging effect. Yang and Yang (2010a) studied single-machine scheduling with simultaneous consideration of job-dependent aging effects, multi-maintenance activities, and variable maintenance durations to minimize the makespan. Yang and Yang (2010b) further considered single machine scheduling with aging or deteriorating effects and deteriorating maintenance activities simultaneously to minimize the total completion time. Yang, Cheng, Yang, and Hsu (2012) studied UPMS problems considering aging effect and multi-maintenance activities (AEMMAs) to minimize total machine load. These studies have primarily formulated the problem with a single objective model. Very little work has focused on multi-objective scheduling problems (MOSPs).

Multi-objective decision making (MODM) techniques have attracted a great deal of interest due to their adaptability to real-life decision making problems. MODM problems often involve multiple conflicting objectives (Majazi Dalfard & Mohammadi, 2012; Zhang, Li, & Xiong, 2012) and decision makers (DMs) are required to search for a trade-off between the objectives. Generally, the MODM problem can be formulated as follows:

$$\text{MODM}:\begin{cases} Min \text{ or } Max: & \{f_1(x), f_2(x), \ldots, f_k(x)\} \\ s.t: & X \in S = \{X \in R^n | g(x) \leqslant b, X \geqslant 0\} \end{cases}$$

In this study we consider the following conflicting objectives: minimizing the makespan, minimizing the total maintenance cost, minimizing the maximum tardiness time of the jobs and minimizing the maximum earliness time of the jobs. In the proposed approach, a MODM problem is reduced to a bi-objective problem by using the technique for order preference by similarity to ideal solution (TOPSIS) (Khalili-Damghani, Sadi-Nezhad, & Tavana, 2013). Next, the resulting bi-objective problem is solved with goal programming (GP) to find solutions that simultaneously have a minimum distance from the positive ideal solution (PIS) and a maximum distance from the negative ideal solution (NIS).

The rest of the paper is organized as follows: In Section 2 we introduce an integrated three-stage maintenance scheduling model for UPMs with AEMMAs. In Section 3, the problem is formulated as a multi-objective integer linear programming (MOILP) model. In Section 4 we use a numerical example to demonstrate the applicability of the proposed approach and exhibit the efficacy of the procedures and algorithms. Finally, conclusions and future directions are given in Section 5.

2. Proposed model

In this section we describe our three-stage approach for the repairmen selection and maintenance scheduling problem. Note that, before the first phase can be initiated, it is sometimes necessary for the DM to do an initial screening on the list of its potential repairmen. Once a suitable list of repairmen is constructed, the repairmen are evaluated and scored using a fuzzy multi-criteria decision making method in the first stage. In the second stage of the proposed approach, a multi-objective scheduling problem is reduced to a bi-objective problem with the TOPSIS method (Khalili-Damghani et al., 2013). Finally, in the third stage, the resulting bi-objective problem is modeled with goal programming to jointly determine the optimal maintenance frequencies and positions of the repairmen's maintenance activities and the optimal job sequences on the machines with respect to some supplementary constraints imposed on the mathematical model. The general framework for our proposed approach is illustrated in Fig. 1. In the following subsections, the three stages of the proposed model are discussed in more detail.

2.1. Stage 1: Evaluation of the alternative repairmen

Multi criteria decision making deals with the problem of choosing the best alternative, that is, the one providing the highest degree of satisfaction with respect to all the relevant criteria or goals. In order to obtain the best alternative a ranking process is required. AHP is one of the most popular and powerful multi-criteria decision making methods for decision making and has been used for years in service quality assessment. However, the AHP method, first developed by Saaty (1980), was inadequate and defective in handling the ambiguity of the concepts that are associated with a human being's subjective judgment. Therefore, the fuzzy AHP method, which combines traditional AHP with fuzzy set theory (Bellman & Zadeh, 1970), was developed for coping with uncertain judgments (Chen & Hung, 2010; Chiou, Tzeng, & Cheng, 2005; Naghadehi, Mikaeil, & Ataei, 2009) and to express preferences as fuzzy sets or fuzzy numbers which reflect the vagueness of human thinking (Cakir & Canbolat, 2008; Liou, Wang, Hsu, & Yin, 2011). In this study, triangular fuzzy numbers (TFNs) are used to represent the fuzzy relative importance of each alternative and criterion. The triangular fuzzy conversion scale used to convert such linguistic terms into fuzzy numbers in the evaluation model is given in Table 1. A TFN $N^{\sim}$ can be denoted by the triplet (a, b, c) with membership function $\mu_{N^{\sim}}(x)$, which is described as follows: the parameter "b" is the most likely value and the parameters "a" and "c" are the lower and upper bounds that limit the field of possible evaluation, as depicted in Eq. (1).

$$\mu_{N^{\sim}}(x) = \begin{cases} \frac{x-a}{b-a}, & a \leqslant x \leqslant b \\ \frac{c-x}{c-b}, & b \leqslant x \leqslant c \\ 0, & otherwise \end{cases} \tag{1}$$

The fuzzy arithmetic operations on two TFNs M_1 and M_2 derived by Dubois and Prade (1979) are as follows: if $M_1 = (a_1, b_1, c_1)$ and $M_2 = (a_2, b_2, c_2)$ then