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Patient scheduling with periodic deteriorating maintenance on single medical device

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ABSTRACT

In this paper, we study a patient scheduling problem with periodic deteriorating maintenance. The objective is to minimize the number of tardy medical treatment of all the patients. A binary integer programming model is developed to characterize the problem. A three-phase heuristic based on Moore's algorithm is proposed for the problem. Numerical experiments are performed to demonstrate the effectiveness of the proposed heuristic. Results show that the proposed heuristic is able to obtain a relatively good solution in a short computation time. The impact of the key parameters on the performance of the proposed heuristic is discussed. Finally, we develop an earliest due date (EDD) rule based heuristic to optimize another objective, the maximum tardiness, which is more applicable when fairness among patients is considered.

1. Introduction

The medical service requirements continue to increase dramatically as the concept of preventive medicine becomes more and more popular. The 2010 Statistical Bulletin of China's Health Development issued by the Ministry of Health of China said that the total cost of National Health in 2010 was estimated to reach 1.9603 trillion RMB, accounting for 4.9% of the Gross Domestic Product. Nowadays, most hospitals provide full range of medical services such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) examination for people of different genders, ages, and health conditions. Despite record healthcare demands and spending in China, many Chinese still have trouble receiving appropriate medical services in a timely manner. Long waiting times for treatment may harm the patients both directly and indirectly. Apart from the psychological distress for the patient, the possibility that their conditions may worsen during the waiting time is a more serious problem. Therefore, how to effectively schedule the patients in order to minimize the number of tardy medical treatments and the waiting time has become an important issue to the management of healthcare institutions.

On the other hand, with the rapid development of modern technology, medical device has gradually become irreplaceable as to carry out most medical treatments. Healthcare institutions face the challenge of ensuring that the medical device is always in its best condition because a low reliability of the medical device will lead to not only economic losses but also safety issues. Performing preventive maintenance on the medical device periodically could greatly improve their reliability, reduce operating costs, and increase operating efficiency.

In most of the literature related to patient scheduling problem, it is always assumed that a medical device is continually available during the planning horizon. However, in practice, the device may not be available all the time due to preventive maintenance. Scheduling with maintenance to prevent machine's premature failures and improve its efficiency has received increasing attentions and been discussed in literature. Schmidt [1] and Ma et al. [2] provide comprehensive reviews on the scheduling problem with deterministic machine availability constraints. In their studies, they both include single machine problem, parallel machine problem, and flow shop problem. Ma et al. [2] also review open shop problem and job shop problem. Lee and Liman [3] study the single-machine scheduling problem of minimizing the sum of job flow-time subject to scheduled maintenance and established a proof of NP-hardness for the problem. Liao and Chen [4] investigate a single-machine scheduling in which periodic maintenance is required, and proposed a branch and bound algorithm and a heuristic algorithm for the objective of minimizing the maximum tardiness. Low et al. [5] study the same problem. They developed a two-phase integer programming model and proposed two heuristics. Lee and Lee [6] propose a heuristic algorithm to minimize total completion time.

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Minimizing the number of tardy jobs is one of the most commonly used criteria in scheduling literature. Moore [7] gives an optimal solution for the single-machine scheduling problem that does not require maintenance with the objective of minimizing the number of tardy jobs. Chen [8] and Lee and Kim [9] both study single-machine scheduling problem that requires periodic maintenance activities with the objective of minimizing the number of tardy jobs and develop two heuristic algorithms based on Moore's algorithm.

Additionally, most research on scheduling with maintenance assumes that the maintenance duration is constant. However, these assumptions may be inappropriate in many situations because maintenance durations may depend on the past running time of the machine. The later the maintenance activity is performed, the worse the machine conditions are. As a result, a longer time is needed to perform the maintenance activity in order to revert the machine to its initial condition. This kind of maintenance activity is called the deteriorating maintenance activity. In production scheduling, several articles have investigated scheduling with deteriorating maintenance. For example, Kubzin and Strusevich [10] study a two-machine flow shop scheduling problem with no-wait in process to minimize the makespan with a maintenance period on one of the machines. They assume that the maintenance duration is dependent on its starting time and provide a polynomial time approximation solution for the problem. Mosheiov and Sidney [11] explore single-machine scheduling with an option to perform a deteriorating maintenance activity. They introduce polynomial time solution for problems with various objectives. Yang and Yang [12] consider single-machine scheduling with aging or deteriorating effects and several deteriorating maintenance activities. They assume that the maintenance frequency on the machine is known in advance and the maintenance duration is dependent on the running time of the machine. They show that the problems can be solved in polynomial time. Yang et al. [13] study single machine common due-date assignment and scheduling problems with an aging effect under a deteriorating maintenance consideration simultaneously. They prove that the problem under consideration is polynomially solvable. Yang et al. [14] consider single-machine slack due-date assignment and scheduling problems with an aging effect under a deteriorating maintenance consideration simultaneously. They assume that the maintenance duration is dependent on its starting time. They propose polynomial time algorithms for problems with different objectives. Xu et al. [15] consider a makespan minimization problem with linearly deteriorating maintenance on single machine and parallel machine.

Another research stream is to consider the different deteriorating effects. Mosheiov [16] study the deteriorating job scheduling problem on single machine, in which the processing times of the jobs depend on the starting time of the jobs. Moslehi and Jafari [17] and Jafari and Moslehi [18] study a single machine scheduling problem, in which the jobs rather than the machine suffer from deteriorations. The objective is also to minimize the number of tardy jobs. Rustogi and Strusevich [19] consider deteriorating effects in which the processing time of each job increases as the processing state of the machine decreases. The maintenance activity may restore the state of the machine, either completely or partially.

In this paper, we consider the patient scheduling with periodic deteriorating maintenance on a single medical device. Ondategui-Parra et al. [20] consider “examination volume” and “examination volume by resource or device” as important productivity-related indicators used by radiology departments to evaluate departmental performance. Abujudeh et al. [21] also treat the “number of patients imaged” as one of the corresponding key performance indicators (KPI) for radiology departments. The objective in this study is to determine a schedule for a fixed number of patients with associated deadlines, minimizing the total number of tardy medical treatments. The objective function captures the main concerns of the hospital when it is too risky to treat the patients after their deadlines. In this case, those patients whose deadlines could not be met will be transferred to other medical facilities to get treated on time. Thus, the number of tardy jobs in our proposed model equals to the number of transferred patients. The hospital would like to accept as many patients as possible to keep its equipment highly utilized for financial reasons. And, to turn away a patient could also hurt the reputation of the hospital. This patient scheduling problem is more complicated than the single machine periodic maintenance scheduling problem to minimize the number of tardy jobs. Since the single-machine scheduling problem with only periodic maintenance activities is shown to be NP-hard by Lee and Kim [9], our problem is also a NP-hard problem. The model settings are similar to Xu et al. [15]. However, different objective function is adopted for real life application concern.

We also consider the scenario in which the delayed patients will not be transferred. Then it would not be fair to violate their deadlines too much. In this case, we modify our objective function to minimize the maximum tardiness. One of the early works studying this objective is by Jackson [22]. In recent years, Luo and Chu [23] develop a branch-and-bound algorithm to minimize the maximum tardiness when sequence-dependent setup times on single machine are considered. Cheng et al. [24] consider the deteriorating effects of jobs on single machine to minimize the maximum tardiness. Sbihi and Varnier [25] investigate two maintenance strategies on single machine to minimize the maximum tardiness.

The contributions of this paper are four-fold. First, we develop a single machine scheduling model to study the patient scheduling problem. The periodic deteriorating maintenance activities are integrated into the proposed model to make it more realistic. Second, we propose a three-phase heuristic algorithm based on the problem properties we discover to minimize the number of tardy treatments in a short computation time. Third, maximum tardiness is minimized when fairness among patients is concerned using an earliest due date rule based heuristic. Fourth, our work will support the patient scheduling decisions of the healthcare institutions in their daily operations to increase patient satisfaction and improve healthcare quality.

The rest of the paper is organized as follows. Section 2 describes the problem and presents the concepts of periodic maintenance and deteriorating maintenance. Section 3 develops a binary integer programming model. Section 4 proposes a three-phase heuristic algorithm based on some properties of the problem to minimize the number of tardy jobs. Section 5 develops an earliest due date rule based heuristic to minimize the maximum tardiness. Section 6 evaluates the heuristic algorithms using a series of computational experiments. Section 7 concludes the paper and discusses some directions for future research.

2. Problem description

The problem considered in this study can be formally described as follows: There are a set $P=\{P_1, P_2, \ldots, P_n\}$ of n patients to be served on a single medical device. Their medical treatments are independent and available at time zero. Preemption of the treatments is not allowed. The treatment of patient i has a processing time p_i and a deadline d_i, which are determined based on the patient's class and his degree of urgency. If a medical treatment is finished after its deadline, it is called a tardy medical treatment. Otherwise, it is called a non-tardy medical treatment.

In addition, the medical device needs to be maintained in order to improve its efficiency. This study considers periodic maintenance