Computers & Industrial Engineering 98 (2016) 30–39

Contents lists available at ScienceDirect

Computers & Industrial Engineering

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

Overhaul planning and exchange scheduling for maintenance services with rotable inventory and limited processing capacity

Murat Erkoc [a,*], Kadir Ertogral [b]

[a] Department of Industrial Engineering, University of Miami, 1251 Memorial Drive, Coral Gables, FL 33146, USA
[b] Department of Industrial Engineering, TOBB University of Economics & Technology, Söğütözü Cad. No: 43, Ankara 06560, Turkey

ARTICLE INFO

Article history:
Received 27 November 2015
Received in revised form 10 May 2016
Accepted 11 May 2016
Available online 13 May 2016

Keywords:
Maintenance planning
Rotable inventory
Full-delay scheduling
Earliness
Aviation

ABSTRACT

Maintenance, repair and overhauling (MRO) of high cost equipment used in many industries are typically subject to regulations set by local governments or international agencies. For example in the aviation industry, critical equipment must be overhauled at certain intervals for continuing permission of use. As such, the overhaul must be completed by strict deadlines. Since the overhaul is typically a long process, MRO companies may implement exchange programs where they carry so called rotable inventory for exchanging expensive modules that require overhaul so that the equipment can continue its services with minimal interruption. The extracted module is overhauled in a capacitated facility and rotated back to the inventory for a future exchange. Since both the rotable inventory and the overhaul process capacity are limited, it may be necessary to carry out some of the exchanges earlier than their deadlines. Early exchanges results in a decrease in the maintenance cycle time of the equipment, which is not desirable for the equipment user. In this paper, we propose an integer programming model so as to minimize total earliness by generating optimal overhaul start times for rotables on parallel processing lines and exchange timetables for orders. We show that the LP relaxation of the proposed model has the integrality property. We develop a practical exact solution algorithm for the model based on a full-delay scheduling approach with backward allocation. The proposed procedure is demonstrated through both a numerical study and a case study from the airline MRO service industry.

1. Introduction

Industrial maintenance and repair includes all the technical and managerial activities carried out to keep a production or service resource available, functional, and safe. Industrial maintenance is especially important in capacity intensive industries with sizeable investments, such as airlines, wafer fabs, and railways. In airlines industry, in particular, maintenance repair and overhaul (MRO) operations are crucial for both ensuring safety and reducing operational disruptions. The maintenance activities are usually subject to regulations and scrutiny enforced by governments or international organizations. Both military and commercial aircrafts must go through MRO at certain intervals defined by either time or flight volume.

The effective management of MRO is not only important in regards to quality and safety, but also from the economic sustainability perspective of the airliners. MRO operations constitute a significant cost item especially in the aviation industry with a substantial business volume (Guajardo, Cohen, Kim, & Netessine, 2012). Therefore, airline companies focus on reducing MRO costs while ensuring that they do not compromise the safety of the airplanes that they operate. Airline companies either carry out MRO in their in-house facilities or outsource it to independent MRO service companies. An important MRO cost factor for airline companies is the disruption of the use of equipment during the MRO process. For example, in the commercial airline industry, the opportunity costs due to downtimes of the planes can amount from a few ten-thousands to hundred thousand dollars per day, depending on the type of the plane and its commercial use. Therefore, reducing turnaround time (TAT) is a key objective in MRO planning.

Inventory management is a crucial factor in MRO for reducing TAT. An important difference between a typical manufacturing system and a MRO system is the fact that MRO systems use so called rotable component inventories or modules, in addition to the regular inventory items (expendables). The rotable inventories consist of expensive components or modules that can be used as loan-outs or exchanges with the customers. The exchange minimizes the TAT

* Corresponding author.
E-mail addresses: merkoc@miami.edu (M. Erkoc), kertogral@etu.edu.tr (K. Ertogral).

http://dx.doi.org/10.1016/j.cie.2016.05.021
0360-8352/

for the airplanes as it only consists of the time spent for uninstalling the used module and installing the new module, without any delays due to other MRO processes. Here we do not consider uninstallation or installation activities of the components, assuming that these activities are carried out by a separate team or production unit, and we only tackle both scheduling of the overhauls and planning the exchanges of rotables.

The exchanged module that requires overhaul joins the MRO firm's rotable inventory and, directly or after some waiting period, enters the overhaul process. Once the overhaul process is completed for the component, it is ready to be used for a future exchange. Thus, the total number of rotable components in MRO system is always constant and a rotable component is in one of the three states; awaiting overhaul, undergoing overhaul process, and ready-to-exchange. The exchange and overhaul schedules determine the formation of these states for all rotables. On one hand, MRO companies aim to operate with low levels of the high-value rotable component inventories to avoid high costs. On the other hand, they must ensure adequate level of customer service.

As pointed out above, the interval times between consecutive MRO's for airliners are strictly regulated. These intervals often times are translated into hard deadlines for MRO services that cannot be violated. For example, the requirement to remove and overhaul a landing gear is every 8–15 years depending on aircraft's use and model. From the cost efficiency perspective, airline companies prefer using this interval times fully and do not want to stop the cycle shorter than the enforced duration. However, the MRO facilities may be compelled to ask some of their customers to bring their airplanes for MRO earlier than their end of cycles due to limited inventory and process capacity. Although feasible, this is not preferable for the airline companies. As such, MRO firms need to efficiently schedule their overhaul operations under their given rotable inventory and process capacity limitations, with the objective of minimizing the early exchanges. In this work, we precisely address this problem.

For a given set of required overhauls and their due dates by the airliners, we propose an integer programming model that minimizes the total earliness under rotable inventory and process capacity constraints. In this context, earliness is defined as the difference between the required exchange deadline (end of cycle) for a rotable in an airplane and the scheduled exchange date for that equipment. Ideally, there should be no gap between the deadlines and the actual exchange dates. However, due to limited number of rotables and processing lines, a gap may be inevitable to obtain a feasible solution where no exchange deadlines are violated. We show that the LP relaxation of the proposed mathematical model has the integrality property. As such, the optimal solution can be directly obtained from the LP relaxation of the model.

We also propose a practical exact solution algorithm based on a so called *full-delay* scheduling for the problem, which can be easily implemented without the need of using any mathematical solver or special computer software. We illustrate the algorithm's implementation using a real-life problem and present a sensitivity analysis that investigates the joint impact of capacity and rotable inventory on the optimal exchange and overhaul processing schedule.

In the next section, we discuss the relevant literature. In Section 3, we present the proposed mathematical programming model. We discuss the properties of the optimal solution and present our exact solution algorithm with an illustrative example in Section 4. In Section 5, we apply the solution algorithm on a case based on real life application from an MRO service company, and investigate the impact of rotable inventory and processing capacity on the optimal solution. We present our conclusions in Section 6.

2. Literature review

Over the past couple of decades a significant volume of research tackled problems regarding MRO management from a variety of viewpoints. Early work in MRO area is generally about planning activities for internal MRO needs in a company. Dekker (1996) summarizes this line of research. The author underlines that most of the models and solution approaches were introduced in 80s and 90s and estimates a growing role of MRO in the future due to increased use of high capital equipment both in manufacturing and service sectors. In a following work, Dekker and Scarf (1998) discuss applications of several models in MRO area and shows the importance of the optimization models in MRO in comparison to the use of more qualitative approaches. They demonstrate the power of analytical models needed to tackle complex problems prevalent in MRO management. A more recent review is reported in Nicolai and Dekker (2008).

Many studies regarding MRO in aviation in recent years focus on the MRO supply chains specifically pertaining to the spare parts and component inventory management. Related research tackles forecasting spare parts consumption (Ghobbar & Friend, 2003; Regattieri, Gamberi, Gamberini, & Manzini, 2005), inventory control with cost and downtime minimization (Safaei, Banjevic, & Jardine, 2011; MacDonnell & Clegg, 2011; van Jaarsveld, Dollevoet, & Dekker, 2012; Gu, Zhang, & Li, 2015), integrated rotable inventory control and overhaul capacity management (Buyukkaramikli, van Ooijen, & Bertrand, 2013), and strategies for inventory pooling and integration across aviation supply chains (Kilpi & Vepsäläinen, 2004; MacDonnell & Clegg, 2007; Kilpi, Töyli, & Vepsäläinen, 2009).

Our research in this study primarily focuses on MRO planning, where we explicitly incorporate capacity and inventory constraints into the optimal scheduling of the overhaul processes. We specifically consider rotables that can be exchanged with the components that require overhaul so as to eliminate downtimes. The most relevant works to the current study are due to Luh, Yu, Soorapanth, Khibnik, and Rajamani (2005), Joo (2009), Joo and Min (2011), and Arts and Flapper (2015). Luh et al. (2005) suggest a mathematical programming approach that integrates scheduling exchanges and inventory control problems. The solution approach is a Lagrangian relaxation scheme. Unlike our model, in this study the due dates of the overhaul requests are taken as the arrival times, and they did not consider early arrivals of requests. The scheduling part of their work concentrates on planning service activities in order to meet the requests. Again unlike our model, their approach allows delays in satisfying a request with an associated penalty. However, the general tendency in aviation MRO practice is to minimize the delays in meeting requests through exchange policies. Joo (2009) tackles the problem of scheduling exchange of a single type rotable with the objective of minimization of the earliness. Similar to our setting, the rotables are scheduled to be exchanged with rotable components for a given a set of aircraft fleet of similar type with overhaul deadlines. The deadlines are not allowed to be violated to avoid downtimes. As such, the exchanges are to be scheduled no later than their respective deadlines. For a given initial inventory of rotables, the author proposes a polynomial time algorithm that optimally schedules the exchange times and overhaul processes. The generation of the schedule is constrained by the availability of rotable inventory level only. However, his model implicitly assumes unlimited number of processing lines and thus, unlimited maintenance capacity. In another paper, Joo and Min (2011) extend this model by incorporating rotable inventory decision by means of a budget constraint. They employ a goal programming approach, where the due date satisfaction and budget constraints are taken as soft constraints. The resulting