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A three-stage approach for aircraft line maintenance personnel rostering using MIP, discrete event simulation and DEA

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ABSTRACT

Personnel scheduling problems need to cope with personnel preferences, coverage constraints, legal restrictions, and many other constraints. We present a three-stage methodology that can be used to select personnel rosters. In the first stage we generate multiple personnel rosters with a mathematical programming model. In the second stage, the performance of the rosters regarding a number of service criteria is evaluated through discrete event simulation. In the third stage, a ranking is made using data envelopment analysis. The methodology is tested on a personnel scheduling problem for aircraft line maintenance.

1. Introduction

Line maintenance includes regular short inspections of an aircraft between arrival and departure at an airport (Gupta, Bazargan, & McGrath, 2003). Once a flight schedule is established, the maintenance company can assign a maintenance schedule to each maintenance station. Based on this schedule, the company builds a staffing model, considering the fleet type, number and type of maintenance jobs, specific client requests, etc. Efficient personnel scheduling not only can reduce costs, but is also directly related to flight safety issues (Yan, Yang, & Chen, 2004). Maintenance workforce schedules have to meet all safety requirements and time constraints: if timetable punctuality is affected, flight delays as well as extra operating costs are incurred. According to delay analyses carried out by Eurocontrol, around 50% of delays are due to airline operational processes, while the remaining delays are due to other causes such as air traffic control, weather and airport capacity constraints (Eurocontrol, 2011). The proportion of intra-European flights delayed by more than 15 min has decreased in the past few years (CODA, 2010). Nevertheless, it was still larger than 15% in 2009 (CODA, 2010). Those delays can have a major impact on airline operations in general and line maintenance operations in particular. Late maintenance that causes primary delays implies causality delays at other airports and huge costs as a consequence. The workforce schedules should be able to prevent this.

Real-world personnel scheduling problems are typically overconstrained. One has to consider coverage constraints, personnel preferences, workload balancing, legal restrictions, etc. Most papers try to mimic this behavior with multi-objective programming. A mathematical programming model is used to generate an optimal roster regarding these constraints and (weighted) objectives. In this paper, we present an alternative way of tackling personnel scheduling problems by using mathematical programming, discrete event simulation and data envelopment analysis (DEA). With this approach, the company is supplied with detailed information about the rosters, which they can use to make the selection objectively. First, a mathematical model generates multiple feasible low cost rosters, which are evaluated with simulation. The roster characteristics and the simulation results are then fed into a DEA model which then identifies the efficient rosters.

This methodology is applied to a case study, in which we evaluate airline maintenance workforce rosters in the occurrence of flight delays (i.e., when flights depart after their scheduled time of departure (STD)). These rosters are the results of the mixed integer linear programming (MILP) model of Beliën, Demeulemeester, and Cardoen (2012). In their model, they try to protect the maintenance schedule from flight arrival delays by scheduling no maintenance jobs during a certain time period after the scheduled time of arrival (STA). Also, they introduce a 15% capacity buffer to deal with employee illness and higher than expected workloads. A flight arrival delay could cause such an enlarged workload because the maintenance job has to be completed within a reduced time window. The evaluation of the workforce rosters occurs after simulating flight delays, based on actual arrival data over a complete season. The results retrieved from the simulation model are evaluated with DEA to obtain a number of dominant rosters from which the company can choose.

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The remainder of the paper is organized as follows. Section 2 offers a review of the recent literature on decision-support models for stochastic workforce problems. In Section 3 we present our methodology. Section 4 addresses a case study. We introduce the problem setting and give a description of the simulation model and its results. Next, the DEA-model and its results are discussed. Finally, some conclusions and further research perspectives are offered in Section 5.

2. Literature review

In a recent review paper on personnel scheduling literature (Van den Bergh, Beliën, Demeulemeester, De Boeck, & De Bruecker, 2012), we showed that most papers study deterministic problems. Deng and Lin (2011), for instance, propose an ant colony optimization algorithm in order to solve an airline crew scheduling problem. Their goal in choosing this algorithm is to minimize the total crew costs which consist of rest expenses, required pay for each duty and under-utilized time between duties. However, factors such as capacity, amount of workload and/or timing of the workload are subject to variability in real-life situations. Many researchers utilize scenario analysis to test alternative combinations of the exogenous variables in order to create robust schedules. In so doing, the decision makers are provided with the effects of the variability of the decision-support criterion (Borgonovo & Peccati, 2011). Corominas, Lusa, and Pastor (2004, 2007) formulate a mixed integer linear programming model to allocate the workforce, considering annualized hours. They use a number of scenarios to test the influence of the demand curves and working-week-type parameters. Brunner and Bard (2012) investigate the problem of determining the size and structure of a workforce that faces time-dependent demand and a variety of labor restrictions and work rules. They address several types of scheduling flexibility in different problem instances, including different shift starting times and lengths, the need for lunch breaks and the option of varying the number of days off.

A second and better way to create robust schedules that can cope with the uncertainty occurring in real-life personnel scheduling problems is to incorporate this uncertainty into the decision-making model. This method is common in call center applications, where the workload depends on the distributions of call arrivals and durations (e.g., Atlason, Epelman, and Henderson (2004, 2008), Avramidis, Chan, Gendreau, L'Ecuyer, and Pisacane (2010), Avramidis, Chan, and L'Ecuyer (2009)). This method can also be used in all types of service organizations. Bard, Morton, and Wang (2007), for instance, address a staff planning and scheduling problem that arises at United States Postal Service (USPS) mail processing & distribution centers (P&DCs) and develop a two-stage stochastic integer program. In the computational phase of the work, three scenarios are considered: high, medium and low demand. The resulting stochastic optimization problem is a large-scale integer program that embodies the full set of contractual agreements and labor rules governing the design of the workforce at a P&DC. The paper of Mason, Ryan, and Panton (1998) details a simulation and optimization-based system for the personnel scheduling (rostering) of customs staff at Auckland International Airport, New Zealand. The approach starts with a simulation system embedded in a heuristic search to determine minimum staffing levels. Next, these requirements are used in an integer programming model in order to optimally allocate staff to each period of the working day. These shifts are then assigned to daily work schedules. This method ensures that all passenger processing targets are met by creating high-quality rosters and has resulted in significant labor cost savings. Yeh and Lin (2007) shorten patient waiting times in a hospital emergency department (ED) by adjusting nurses' schedules. They use a simulation model to cover the complete flow for the patient through the ED. The results from the simulation are then fed into a genetic algorithm that makes adjustments to the nurses' schedules. Their results indicate that the average waiting time when using the staffing plan can be reduced significantly.

In reviewing the literature, we noticed that authors are eager to explain the structure of the algorithms developed to create feasible personnel schedules, but only little is known about how good those schedules actually are. Frauendorfer and Königsperger (1996) present a framework for the improvement of (production) scheduling decisions in chemical processing environments using multi-criteria analysis. The purpose of the framework is to provide complete scheduling performance transparency and to contribute to better decision making. Ruiz-Torres, Ho, and López (2006) address a supply chain scheduling problem where both internal and external/outsourced parallel resources are available and the objectives are to minimize the number of late orders and the total outsourced machine time. Several heuristics are developed that generate sets of Pareto-efficient schedules. The evaluation (comparison of the heuristics) is based on two experiments where the values of relevant parameters (e.g., due date tightness or number of jobs) are set at different levels.

In our paper, we want to consider cost minimization and service maximization simultaneously, together with other criteria. One way of dealing with multiple criteria is through multi-objective optimization. Tsai and Li (2009) develop a two-stage mathematical model for a nurse scheduling system. Their genetic algorithm deals with both hospital management requirements and nursing staffs' shift preferences. A different approach is used by Castillo, Joro, and Li (2009). They depart from the standard in workforce scheduling to minimize the cost of labor subject to a target service level. They argue that this single operational measure is neither sufficient for capturing the performance of service organizations, nor for characterizing and quantifying service quality. In their approach, they generate a large number of plausible schedules to be evaluated with multiple criteria. Among the evaluated schedules, the efficient ones are identified and the best one is chosen. For the evaluation of these schedules, they use a Free Disposable Hull algorithm. This approach enabled the management to transform their needs into efficient schedules and to understand the relationship between the cost of labor and various service-quality criteria. The final stage is rather uncommon in the literature. The previously mentioned paper of Yeh and Lin (2007) ends with the remark that their results "can be provided to the hospital administrators for use in decision-making towards enhancing patient care and staffing". The administrators have to choose between schedules with two shifts and those with three shifts and are provided with simulation results for both alternatives. In our approach we want to facilitate this step by incorporating an evaluation stage for the different personnel rosters.

Instead of a Free Disposable Hull algorithm we will use DEA to evaluate the different rosters. DEA is a method used to determine the relative efficiencies of a set of organizational units, defined as decision making units (DMUs), considering multiple inputs and outputs (Charnes, Cooper, & Rhodes, 1978). Examples of such units to which DEA has been applied are: banks, police stations, hospitals, tax offices, prisons, defense bases (army, navy, air force), schools and university departments. In our study, we will consider the rosters as decision-making units, each with its own inputs and outputs. For the selection of the inputs and outputs and the specific DEA-model, we checked the paper of Dyson et al. (2001). They provide some pitfalls that have been identified in application papers and suggest protocols which can be used in order to avoid these pitfalls and to guide the application of the methodology.