Technical Report

Scheduling, Revenue Management, and Fairness in an Academic-Hospital Radiology Division

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Rationale and Objectives: Physician staff of academic hospitals today practice in several geographic locations including their main hospital. This is referred to as the extended campus. With extended campuses expanding, the growing complexity of a single division's schedule means that a naive approach to scheduling compromises revenue. Moreover, it may provide an unfair allocation of individual revenue, desirable or burdensome assignments, and the extent to which the preferences of each individual are met. This has adverse consequences on incentivization and employee satisfaction and is simply against business policy.

Materials and Methods: We identify the daily scheduling of physicians in this context as an operational problem that incorporates scheduling, revenue management, and fairness. Noting previous success of operations research and optimization in each of these disciplines, we propose a simple unified optimization formulation of this scheduling problem using mixed-integer optimization.

Results: Through a study of implementing the approach at the Division of Angiography and Interventional Radiology at the Brigham and Women's Hospital, which is directed by one of the authors, we exemplify the flexibility of the model to adapt to specific applications, the tractability of solving the model in practical settings, and the significant impact of the approach, most notably in increasing revenue by 8.2% over previous operating revenue while adhering strictly to a codified fairness and objectivity.

Conclusions: We found that the investment in implementing such a system is far outweighed by the large potential revenue increase and the other benefits outlined.

Key Words: Revenue management; personnel scheduling; fairness; mixed-integer optimization.

With the introduction of the extended medical campus to today's hospitals, the complexity of physician schedules has dramatically increased as department members who have historically been confined to a single institution and location are now routinely spread across an entire region. At the same time, there are important concerns associated with assigning a physician to a daily assignment. The average revenue yielded from assigning one physician to an assignment may differ somewhat from assigning another physician to the same or different assignment. This affects both the departmental revenue and the physician's own revenue, and therefore, there are immediate concerns for fairness in the income of the department's physicians. It also means that a naively optimal schedule that maximizes total revenue without considering fairness will also enlarge the disparities in individual revenues and not offer equal opportunities to practice at varied locations. Other concerns include individual site and practice preferences, time-off requests, physician effort and fatigue, and the distribution of on-call assignments. These entail both strict limitations on possible schedules and softer fairness concerns in accommodating all the physicians equally.

Thus, deciding whom to place where in an extended medical campus is a complex exercise that takes many considerations into account. Failure to successfully mitigate all of these concerns will on the one hand overexert the physicians and create unfairness and on the other generate poor revenue for the department. Inequity, in turn, entails disincentivization, lowers employee satisfaction, and is simply unacceptable based on business principles. Where whole departments are worth in the hundreds of millions of dollars of revenue per year to a hospital, missing out on a few percentage points due to improper scheduling amounts to a large loss.

For these reasons, this is a problem of considerable and growing importance for many medical departments where the extended medical campus is expanding. At the same time, this significance is often overlooked, and this scheduling problem has not been addressed from optimal scheduling, revenue management, or quantitative fairness perspectives,

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traditionally being done somewhat informally by hand, without clear quantifiable objectives and with poorer results as the task increased in sophistication over time.

One of the authors (R.B.) is the Herbert L. Abrams Director of the Division of Angiography and Interventional Radiology at the Brigham and Women's Hospital, Boston, Massachusetts (mentioned as BWH IR henceforth) and has the responsibility of managing the physician staff and the overall revenue of the division. In particular, he is responsible for the daily scheduling of the eight physicians in the division, himself included. With the academic responsibilities of a teaching hospital affiliated with Harvard Medical School and an extended campus that includes three external clinics in Boston suburbs in addition to the facilities at the hospital, BWH IR faces a formidable scheduling task with great implications for the physician staff, their revenue, and the departmental revenue.

The present article is motivated by the need of studying these tasks and their ramifications on revenue and human resources from an operational and quantitative point of view. To our knowledge, this is a novel consideration of the problem in the literature, incorporating aspects of disciplines in which operations research has a proven track record of success, including scheduling, revenue management, and quantifying fairness. As a complex operational planning task with direct impact on revenue and fairness, scheduling the daily assignments of the physician staff of a medical department could benefit greatly from operations research.

RELEVANT LITERATURE

Personnel scheduling is a well-studied problem in the literature and one in which operations research, and particularly optimization, has offered success. There are a myriad of special problems, solutions, and studies. We refer the interested reader to Ernst et al. (10) for an exhaustive review and annotated bibliography of studies of personnel scheduling. There is in particular a significant amount of work on scheduling nurses (9,10,14) and on scheduling physicians in an emergency room (2,7) that also focuses on lower level structures such as the timing of shifts. Notable examples of applying mixed-integer optimization (MIO) methods to personnel scheduling problems in other domains are Stojkovic et al. (16) and Caprara et al. (6).

In addition, there have been studies of fairness in scheduling, mostly in the context of computer process scheduling and scheduling transmissions over communication networks. A few notable examples are Hahne (11), Liua et al. (13), and Zaharia et al. (17). Fairness has also been studied in other operational applications ranging from travel arrangements for National Basketball Association games (1) to allocations of kidney transplantations (4).

Fairness has also been studied abstractly in the generic context of utility allocation by a central decision maker. In the study by Bertsimas et al. (3), the authors seek to bound the inefficiency of fairness, or the relative difference between the social optimum and different fair allocations. For a thorough review of the philosophical and mathematical studies of fairness over the years, we refer the reader to the references in Bertsimas et al. (3) under section 3.

CONTRIBUTIONS AND STRUCTURE OF ARTICLE

We here argue that this overall scheduling and revenue management problem is amenable to solution by mathematical optimization. Quantifying the above considerations and nontangible partialities as variables and constraints using existing theory allows for a computable mathematical solution that not only generates feasible schedules but also chooses the most desired one in some sense, such as maximal revenue and minimal mismatch with individual scheduling preferences. We propose a simple unified optimization formulation using MIO that is flexible, efficiently solvable in practical settings, and impactful.

These qualities are exemplified through the motivating case for this study, BWH IR, where the optimization approach is implemented. In particular, the scheduling procedure is successfully implemented and incorporated into the workings of the division. Scheduling optimally in this way offered an increase of 8.2% in projected departmental revenue, amounting to a considerable improvement given the significant revenue already generated by the division. The schedule adheres strictly to a codified fairness, and we observe empirically an improvement in various measures of inequity. We find that compared to the initial fixed cost of implementing such a scheduling system including the costs of solver software, the clear revenue gains are far greater, not to mention the potential gains in fairness and employee incentivization and satisfaction.

The structure of the article is as follows. In the next section, we present the problem as motivated by the case of BWH IR. We then proceed to review the Materials and Methods used in addressing it. In Fairness Considerations we discuss the fairness considerations in the problem and discuss the mathematization of fairness and its implications. In The Extended Campus at the Division, we describe the structure of the extended campus at BWH IR as it pertains to the scheduling problem. In Data and Inputs, we discuss the data we use in the case of BWH IR. In Mathematical Formulation section, we present the generic unified formulation of the problem as an MIO. In Implementation at BWH IR, we discuss the implementation of the proposed methodology to the specific case of BWH IR, discussing both adapting the optimization model to this case and also practical considerations of actually carrying out the implementation. We then discuss the results we observed in this application in Results. Finally, we offer some concluding remarks in Discussion.

THE EXTENDED CAMPUS AT THE DIVISION

The Department of Radiology at BWH consists of 176 physicians practicing in nine locations including the main