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Chapter 5
Resident Scheduling in Teaching Hospitals

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Abstract After graduation, physicians receive further training in a medical domain like anesthesiology. There are 57 medical specialties in Germany in total. The high cost pressures of hospitals and the changing view of the medical profession regarding the work-life balance have led to recruitment problems and low employee satisfaction in many places. A promising approach to counter this problem is objective and structured training planning. This research project mainly deals with medical residents' strategic and tactical-operative training scheduling. In addition to relieving the medical staff currently responsible for the planning process, this research project increases the predictability of structured training. This allows hospitals to increase the quality of their training and, consequently, their attractiveness to other hospitals. In addition, supervisors from different departments can better assess residents' knowledge and thus keep the level of service, which is particularly important in hospitals, permanently high even when changing residents. From the residents' point of view, a well-structured training schedule enables a high degree of information. Therefore, residents are no longer surprised by a short-term change of department and have a direct insight into their training progress. A real-world case study evaluates the mathematical formulations and the solution approaches.

Keywords OR in health services · Mixed integer programming · Real-world application · Stochastic optimization

Motivation

After graduation, physicians receive further training in a medical domain like anesthesiology or urology. There are 57 medical specialties in Germany in total, in which further training as a specialist is possible. Physicians are called residents in this special phase of training. In Germany, there are about 60,000 residents in specialist

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training [1]. A characteristic of the German model—representative for many non-English speaking countries in Europe—is the training and further education accompanying the work. Entirely in keeping with the "dual training" concept, the residents are deployed in regular hospital operations and are an essential part of the value chain. In contrast to the American or British rotation model, mainly considered in the current literature, the German specialist training lasts longer. It is tied to specific interventions (tasks), i.e., the possibility of training and further education depends on the hospital's treatment spectrum. However, since the occurrence of interventions relevant to the resident program cannot be planned with certainty in advance and therefore is not taken into account in personnel planning, this form of specialist training is subject to uncertainty concerning training duration [2]. The basic formulation of the resident scheduling problem can be described as follows. A function $f{:}I \times J \times T \rightarrow \{0, 1\}$ is sought, which fulfills:

$$\sum_{i \in I} f(i, j, t) = D(j, t) \qquad \forall j \in J, t \in T \tag{5.1}$$

$$\sum_{t \in T} f(i, j, t) = \mathrm{M(i, j)} \qquad \forall \mathrm{i} \in \mathrm{I},\ \mathrm{j} \in \mathrm{J} \tag{5.2}$$

$$\sum_{j \in J} f(i, j, t) = 1 \qquad \forall \mathrm{i} \in \mathrm{I}, t \in T \tag{5.3}$$

Constraints (5.1) ensure that a teaching service $D(j, t)$ must be fulfilled for all rotations $j \in J$ and periods $t \in T$—in personnel planning problems this is often seen as a demand. Rotations can then be described as departments. Constraints (5.2) consider the training requirement $M(i, j)$ that must be met over the entire time horizon. This means that each resident $i \in I$ must fulfill each rotation to a specified extent. Constraints (5.3) ensure that each resident should be assigned to exactly one rotation in each period.

Personnel planning that is not appropriate to the resident training can have two economic consequences, both of which are based on the fact that every resident training provider (hospital) is obliged to guarantee the residents' training in the time allocated. Suppose the resident can prove that the training program must be extended for reasons the provider is responsible. In that case, the hospital must pay a specialist's salary despite the lack of specialist status. In this context, an initial judgment was made in 2015 by the State Labor Court of Baden-Württemberg. It was stated here that an objective training plan must already be available at the start of employment; otherwise, a time limit is not justified [3]. Even more important is the fact that departments that are repeatedly unable to offer the contents of the resident program within the specified time are threatened with restrictions on the authorization of further training by the medical associations. The departments concerned would then have to hire more expensive specialists instead of the more cost-effective residents if available on the market [4].

The main contributions are the following. First, a strategic problem for determining the maximum number of residents is presented, which is able to consider an uncertain set of interventions via a robustness concept. Second, a possibility is described to deal with the uncertainty between annual planning and daily planning by introducing priorities in annual planning. Third, a model is presented to measure the training program's impact on service quality in the departments.

The remainder of this work is as follows. Next, the methodologies will be presented. Afterward, details of the results are discussed. Eventually, it will close with a conclusion.

Methodology

The interventions have an elementary role in the concept of task-related resident scheduling and are an essential innovation to the existing literature in resident scheduling [5]. Since the distribution of the interventions over the planning horizon of 5 years is difficult if at all, to determine, robustness concepts offer an excellent possibility to consider the uncertainty. Historical data over 26 months makes it possible to determine the upper and lower limits of executable interventions per department quarterly. These limits allow the usage of the price of robustness [6] for the model formulation. One of the advantages of this concept is that the mapped uncertainty does not change the model, i.e., if the model is linear, it can also be formulated linear using the price of robustness. This is important because resident scheduling problems are NP-hard [7]. The same applies to this formulation with interventions, which can be seen as a task allocation and sequencing problem with upper and lower bound temporal constraints. Bertsimas and Sim [8] have proven that this type of problem is NP-hard and, therefore, not tractable. Since the problem's block structure suggests using a decomposition based on a Dantzig-Wolfe reformulation, the compact model is decomposed by residents. The result is a master problem that handles each department's capacity and a subproblem that generates feasible training schedules for one generic resident. The decomposition's unique feature is that the robustness concept is completely included in the subproblem, i.e., each solution of the subproblem is robust according to the defined parameters. A sophisticated column generation heuristic that detects near-optimal solutions (on avg. $< 5\%$ optimality gap) within minutes is developed to solve the decomposition (see Fig. 5.1). In particular, a new pattern generation approach for cyclic problems is presented that further decreases solution times significantly. For each subproblem with negative reduced cost, multiple columns are generated by shifting the start period of the generic resident.

A second aspect of uncertainty is considered in the tactical problem of annual resident scheduling by taking absences into account. Due to absences, a resident might be assigned to a department deviating from the training schedule. One approach to take these types of changes into account in the training schedule is using backup schedules, i.e., a resident is assigned to more than one department. Setting different schedules

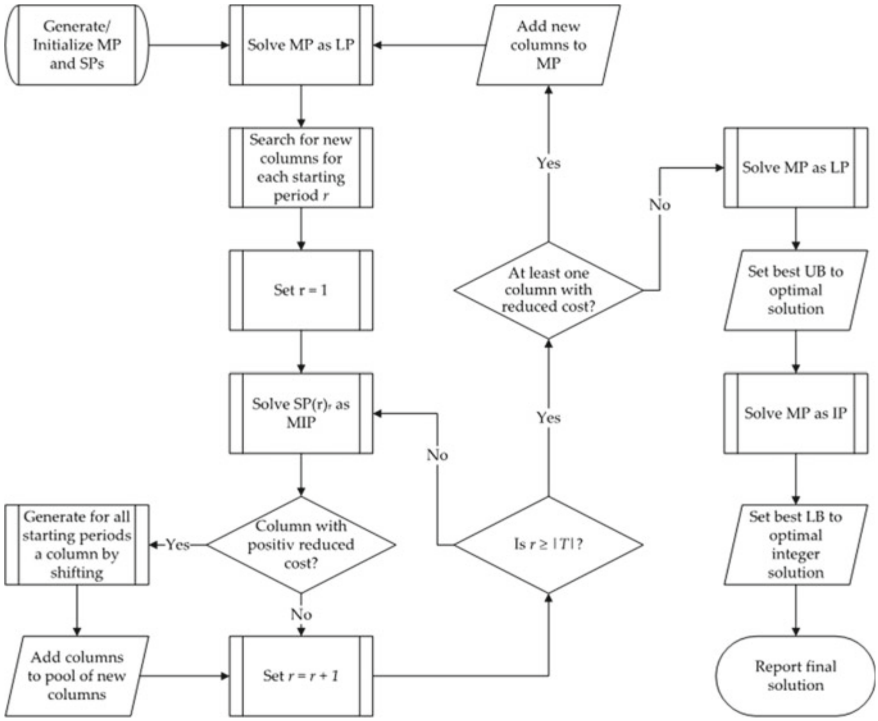

Fig. 5.1 Illustrative flow chart of the column generation heuristic [5]

using priorities gives residents additional information about possible activity fields and ensures that they are not surprised by short-term changes. This kind of training schedule design is not yet considered in the current literature. Therefore, one of the main contributions is the novel mathematical formulation of the annual resident scheduling problem with priorities. The problem is set up as a two-stage stochastic program to map the previously identified absences of residents in the model. Since the deterministic resident scheduling problem is already NP-hard, the stochastic version causes several problems at once. On the one hand, the model cannot be solved with commercial solvers in a suitable time. On the other hand, it fails already because of a finite bound, i.e., the solver cannot determine a linear programming (LP) bound for realistic problem sizes within one hour. Therefore, an analytical bound is derived for the problem. The formulation is decomposed between the first and second stage and integrated into an iterative algorithm to solve the problem.

The violation of continuity is considered in a quadratic formulation of the annual resident scheduling problem [9]. The quadratic formulation is necessary since more changeovers have a stronger effect on the service level. Since non-linear problems are usually more challenging to solve, a linearization of the model is presented. Good, feasible solutions cannot be found in the original quadratic or the linearized formulation within 24 h with standard solvers. For this reason, a metaheuristic approach is used to solve the problem. The genetic algorithm has the advantage that several annual schedules can be made available for selection to the hospital management.

Results

The robustness concept and the integration in a column generation heuristic are tested in a real-world case study of a German university hospital with more than 1,200 beds. The case study shows that the hospital takes a very liberal approach to uncertainty. The hospital trains 84 residents. This value corresponds to approximately a 5% occurrence of the lower limit of interventions per department. Consequently, the hospital is not able to finish the education of all residents on time. The algorithm's performance is analyzed by using 60 instances divided into three different sizes. No significant difference in both the optimality gap and the solution time was found. A comparison of the pattern generation approach showed that the classical column generation took on average 6.1 times longer to solve than the newly developed cyclic approach (see Fig. 5.2). While an increase of the robustness level does not differ according to the problem size, the effect of a change of the robustness level is quite high across all problem sizes, with differences of up to 90%.

The developed algorithm and the analytical bound for the annual resident scheduling problem with absences are analyzed in an experimental study based on the same data set as before. The bounds analysis shows that the analytical bound is superior to the LP bound by more than 8% on average. In addition, it is shown that superiority increases with a rising number of selectable priorities. Besides the analytical bound, an approximation of the upper bound based on the solution algorithm is developed. A parameter is estimated based on numerical tests, which ensures that the approximate bound underestimates the upper bound by a maximum of 12%. However, this does not occur during the entire experimental study. In a further study, the performance of the solution algorithm is analyzed. For this purpose, the algorithm is tested using a cold and warm start as well as a batching approach to reduce the number of scenarios considered in parallel. This study shows that a warm start with the solution of the deterministic problem and in combination with a batching scheme

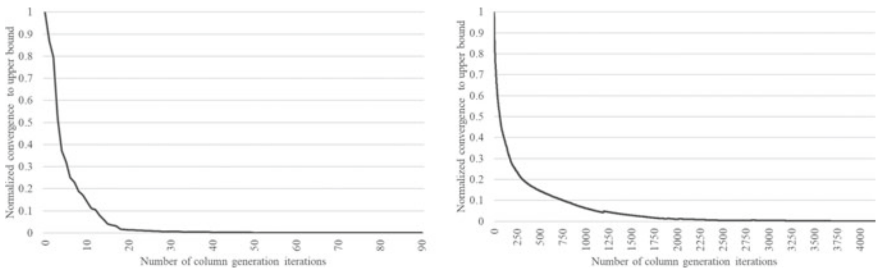

Fig. 5.2 Convergence cyclic pattern generation (left), convergence standard generation (right) [5]

is advantageous both in terms of solution quality and solution time. The results show that a training schedule with two priorities already eliminates almost all unexpected assignments, i.e., from initially over 10% to only 1%. Finally, the study shows that a training schedule with two priorities is already superior to traditional planning with only one priority.

The genetic algorithm is evaluated and compared with standard software solutions analyzing a German training hospital's real-world situation from 2016. When comparing the real-world case with the genetic algorithm's solutions, it becomes clear that the hospital has not exhausted all potentials concerning the objectives investigated. It would have been possible to improve continuity by 25% or improve fair training progress by up to 30%. The analysis of both models and the comparison of the genetic algorithm solutions with those of the standard solver shows that the standard solver solutions are always in the same solution region regardless of the selected objective function weights. This is because the solver often does not get beyond the heuristically constructed start solution within 24 h. It has been shown that the solver has problems finding and improving solutions concerning fair training progress. Even in small instances with only 20 residents, a standard solver could not solve the problem optimally. These results again underline the genetic algorithm's strength compared to the solver for the problem under investigation. Nevertheless, the solver results show that there are possibilities for small instances to sharpen the MIP formulation further to get a good solution. In general, the study shows that the costs for continuity of care and fair training progress are very high in the respective extreme, i.e., improving continuity of care by a small amount has a high impact on the fairness level if the schedule has a good fairness level and vice versa. However, it is also possible to determine a medium range in which the relative improvement of fair training progress is associated with low costs of continuity.

Conclusion

The resident scheduling problem has a unique structure due to the simultaneous demands of departments and residents. According to specialization, hospital, and country, the individual characteristics provide for a large number of variations of the basic model. This work deals with a German case of the resident scheduling problem, which differs from the existing literature by its task-related structure.

The overall goal of the work is to get a deeper understanding of the resident scheduling problem. Current problems such as non-compliance with the duration of training programs are considered. Besides, generalizable interconnections, such as continuity of care or differences between annual and daily planning, are analyzed. The Operations Management literature on resident scheduling can be divided into staffing and rostering decisions, as with other personnel planning problems. However, a large part of the literature deals with the American resident training system, which shows notable differences to the training system investigated in this work. The first contribution combines a column generation method with an existing robustness concept based on surgical data. An advantage of this approach is that decision-makers can define a suitable level of robustness independently. Interventions that are difficult to predict in this time horizon have a fundamental impact on the duration of the training program and the possible number of residents a hospital can employ. Uncertain events, such as absences, are another contribution. In addition, the loss of information due to operational processes' aggregation on a tactical level is considered here. It is shown that the use of priority assignments positively affects adherence to the tactical schedule on an operational level. Planning processes often influence other areas, as well. Thus, the final study shows the influence of departmental changes within the training program and how to deal with them.

To summarize, the socio-economic change on the one hand and medical progress on the other will increasingly present hospitals with new challenges. Residents will play a decisive role in this, representing a more cost-effective alternative to specialists. Therefore, it will become increasingly important to deploy residents effectively and efficiently.

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