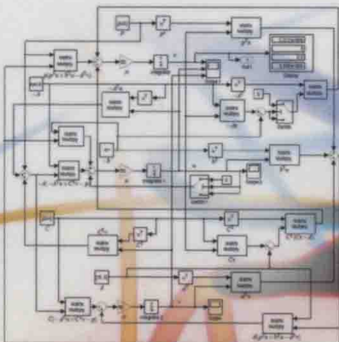
Mathematics Research Developments

Linear Programming

Theory, Algorithms and Applications



Yaromir Truma
Editor

Novinka

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LINEAR PROGRAMMING

THEORY, ALGORITHMS AND APPLICATIONS

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PREFACE

Linear programming (LP), as a specific case of mathematical programming, has been widely encountered in a broad class of scientific disciplines and engineering applications. In view of its fundamental role, the solution of LP has been investigated extensively for the past decades. Due to the parallel-distributed processing nature and circuit-implementation convenience, the neurodynamic solvers based on recurrent neural network (RNN) have been regarded as powerful alternatives to online computation. This book discusses how linear programming is used to plan and schedule the workforce in an emergency room; the neurodynamic solvers, robotic applications, and solution nonuniqueness of linear programming; the mathematical equivalence of simple recourse and chance constraints in linear stochastic programming; and provides a decomposable linear programming model for energy supply chains. (Imprint: Novinka)

Service congestion, bottlenecks, long waiting times, and unbalanced working hours are common problems in many hospitals. Chapter 1 proposes new staffing and scheduling "policies" of qualified workers considering patient daily demand. Three main work stages have been proposed. In the first, the objective is to determine optimal staffing levels for all type of medical workers in each area. In the second phase, workers are assigned to different activities and shifts according to legal and institutional policies. Finally, at a third level, personnel programming is updated in real time according to daily demand behavior. Obtained results show an optimal combination of different types of physicians and nurses needed in the emergency room and their weekly scheduling.

Linear programming (LP), as a specific case of mathematical programming, has been widely encountered in a broad class of scientific disciplines and engineering applications. In view of its fundamental role, the solution of LP has been investigated extensively for the past decades. Due to the parallel-distributed processing nature and circuit-implementation convenience, the neurodynamic solvers based on recurrent neural network (RNN) have been regarded as powerful alternatives to online computation. In Chapter 2, three special kinds of RNNs [namely, traditional primal-dual neural network (T-PDNN), improved primal-dual neural network (I-PDNN), and linear variational inequality based primal-dual neural network (LVI-PDNN)] are presented and investigated for the LP problem solving. Moreover, as a robotic application to inverse-kinematic control, the minimum infinity-norm redundancy resolution, also known as the minimum-effort resolution (MER), explicitly minimizes the largest component of joint variable vectors (e.g., joint velocity, acceleration or torque). It is useful in situations where focuses are on low individual magnitude, even distribution of workload, and analysis of motion diversity. Computer-simulation results based on planar, PA10 and PUMA560 robot manipulators well substantiate the feasibility and effectiveness of the MER schemes and the neurodynamic solvers. At last, for handling the discontinuity problem of minimum-effort inverse-kinematic resolution, the nonuniqueness condition of LP is investigated, and a system of one inequality and two equations is presented for online effective nonuniqueness-checking.

There are two different approaches to stochastic linear programming; two-stage programming and chance constrained programming. In two-stage programming, a shortage or an excess arising from the violation of the constraints is penalized, and then the expectation of the amount of the penalties for the constraint violation is minimized. In contrast, chance constrained programming admits random data variations and permits constraint violations up to specified probability limits. In Chapter 3, we consider the mathematical equivalence between stochastic programming problems with simple recourse and those with chance constraints. As a result, two main theorems are presented. In the first theorem, it is shown that the optimal solution of the chance constrained problem coincides that of the simple recourse problem when the satisficing probability levels are specified in connection with the penalty costs to violating the constraints. As the opposite result, in the second theorem, it is also shown that the optimal solution of the simple recourse problem coincides that of the chance constrained problem when the penalty costs to violating the constraints are specified in connection with the satisficing probability levels. These results give the corresponding relationship between stochastic programming problems with simple recourse and those with chance constraints, and then to make this relation more easily understood we illustrate it with a simple numerical example.

Chapter 4 presents an application of linear programming to an energy supply chain problem. The energy supply chain is composed of the fuel supply market, electricity generators and electricity consumers. A linear programming model is developed to determine the optimal fuel mix for the system under the constraints of suppliers` and generators` capacities, CO_2 emission quota, generators` profit targets and other technical issues. In particular, the Berger Parker Index is considered to measure the fuel diversity index of the supply chain. Then, the model is solved using the Dantzig-Wolfe Decomposition algorithm. The performance of the algorithm, with respect to its computational speed and efficiency, is investigated using various sizes of the energy supply chain model.

Numerical studies have also been performed on a case study concerning four suppliers, four electricity generators, four consumers and four fuel types. The case study shows the capability of the energy supply chain model to determine the best aggregate strategy of fuel mix that would generate electricity according to changing fuel prices, customer demands and profit targets. The model is also used to provide Pareto frontiers, which illustrate tradeoffs between diversity index, profit and emission quota. Finally, it is found that the model can be applied for any areas of energy planning and could also be easily extended to meet specific scenarios.

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Chapter 1

PLANNING AND SCHEDULING AN EMERGENCY ROOM WORKFORCE USING LINEAR PROGRAMMING

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Abstract

Service congestion, bottlenecks, long waiting times, and unbalanced working hours are common problems in many hospitals. This project proposes new staffing and scheduling "policies" of qualified workers considering patient daily demand. Three main work stages have been proposed. In the first, the objective is to determine optimal staffing levels for all type of medical workers in each area. In the second phase, workers are assigned to different activities and shifts according to legal and institutional policies. Finally, at a third level, personnel programming is updated in real time according to daily demand behavior. Obtained results show an optimal combination of different types of physicians and nurses needed in the emergency room and their weekly scheduling.

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Introduction

Planning and programming hospitals resources affect the success of any medical attention and therefore the patient satisfaction level. The lack of any equipment, medical supply, or human resource when needed may affect patients' health, integrity and even their quality of live. On the other hand, any excess of these resources perturbs the hospital financial stability because those resources are very specialized and therefore expensive. This work proposes two models to determine the optimal combination of nurses and medical staff for the emergency area and their scheduling constrained by several legal and institutional polices.

Current Situation

The studied hospital emergency area presents a diverse number of problems related to its personnel planning and programming. This area has high patient congestion (a daily demand around 300 patients), bottlenecks and long waiting times in some areas like triage, high stress levels in their medical staff and unbalanced working hours. This area also receives the highest number of complaints, 81% of all survey patients indicate that their main complaint is the slowness of the service (more than 3 hours of waiting in the area). This problem is common in most hospitals' emergency areas, patients in many cases get desperate and leave the system before receiving medical attention, affecting hospital image.

This hospital does not have any study that allows determining their optimal medical staffing levels according to their daily demand. In fact, the only study they had was about the number of activities assigned to each worker without considering the patient demand. Perhaps, if the current medical staff level were based on a study which considers the patient demand, they could avoid some issues as unidentified bottlenecks and they could optimize their patients flow and satisfaction levels.

This approach gives a solution to the staff configuration. With the proposed model, it is possible to estimate the optimal assignation of physicians and nurses to working shifts. A hospital needs to establish a constant number of workers for every period per year. The area behavior has been studied through the analysis of times, activities, patient demand, patient classification and type of physicians and nurses.

In order to achieve this goal, a linear programming model has been developed. It minimizes the total amount of workers in order to reduce staff cots and satisfying the patient demand requirements, it also satisfies that some areas must get covered with the right personnel even if they do not receive any patient. Then, another model is proposed to obtain their scheduling according to a large number of legal and institutional constraints.

Background

This study was developed in the emergency room of a private hospital in Bogotá, Colombia. The current situation in this hospital reflects that there was not any study that allows the hospital to determine its human resource requirement, therefore some problems as unidentified bottlenecks, long waiting times, and constant complaints from patients are a common daily issue. The current personnel staffing and scheduling is done manually which carries a lot of problems. Among them, the time that nurses and physicians can spend on patients care is reduced for doing administrative tasks, for example nurses' scheduling may take to the nurses' head about 30 hours for only a month schedule. Besides, it is a difficult task because there are many policies that they must consider in order to generate these assignments. Therefore, the obtained results are not the expected ones due to the difficulty to fulfill all the requirements like the balanced working hours between workers.

A literature review reflects that there is little evidence of studies that determine hospitals staffing levels.

Personnel planning and programming in hospitals is a time consuming but vital activity. A badly designed programme or simply a mistake in respect of the number of required workers could produce high patient congestion, bottlenecks and/or long waiting times in some areas. In addition, other associated problems could include high stress levels amongst medical staff and unbalanced working hours.

In order to reduce these problems, one strategy is to identify the number of personnel needed by considering demand behaviour and the characteristics of each task – referred to as "the planning problem." After that a programme can be generated for each member of staff on a temporal planning horizon – referred to as "the scheduling or rostering problem."

The literature review tells us that most publications on rostering in health systems focus mainly on nurse rostering problems. The resolution of these problems is geared to providing a suitably qualified quantity of nurses to cater for often competing issues (such as the demands of work regulation, balancing workload, allowing days off and employee preference). The generation of a roster in nursing services is highly time consuming. This is because it is usually produced manually by nurses who are faced with several difficulties in building a valid program. Because of this, unbalanced programs are the usual result. This is why, in many studies, the objective is to provide a decision support system to reduce the time taken designing the programme.

In general, in respect of nurse rostering problems, it is possible to consider two different types of scheduling. Firstly, cyclic scheduling - where each nurse follows the same pattern during different scheduling periods and, secondly, noncyclic scheduling - where a new schedule is generated in each scheduling period.

To solve this problem and find a valid schedule each nurse requires an individual schedule but the overall schedule must satisfy overall demand. These include, amongst others, mathematical programming, classical heuristic and metaheuristic etc. Cheang et al. (2003) presented a classification of the nurse rostering problem in light of the objective function together with the constraints and solution approaches. Ernst et al, 2004 identified 28 categories of solution methods to solve the nurse rostering problem. In general, it is possible to extend this conceptually so schedules can be created not only for nurses, but also for medical staff and other emergency staff members.

Some authors propose the use of mathematical programming to solve the nurse rostering problem. Among the approaches used are decomposition methods (column generation and Bender's Decomposition being most relevant, in this context). These methods are used to generate feasible sets of schedules and to find optimal allocation of resource (Kostreva and Jennings 1991; Millar and Kiragu 1992; Demeulemeester and Beliën 2008). Jaumard et al. (1998) have presented a column generation approach to solve the problem. In their model, the auxiliary problem objective identifies an acceptable schedule for a given nurse whilst respecting collective agreement requirements such as seniority, workload, rotations and days off. The master problem tries to identify a configuration of individual schedules while meeting demand coverage constraints, minimising salary costs and maximising nurse preferences and team balance.

Almost all proposed methods to solve the nurse rostering problem have some factors in common. Firstly, the methods look for a feasible set of schedules for every nurse, while minimizing the resource needed to meet demand (Kostreva and Jennings 1991; Demeulemeester and Beliën 2008;Jaumard et al. 1998; Warner and Prawda 1972;Warner 1976). Secondly, these approaches look for an optimal allocation of resources maximizing coverage in respect of planning horizons and trying to include other constraints such as aversion of personnel to their schedules, seniority, workload, rotations and days off and so on. Warner and Prawda (1972), solved the problem using large-scale mixed integer cuadratic programming and multiple-choice programming that quantified, in its objective function, the specifications previously mentioned.

When it comes to multiobjective approaches, it is possible to find a group of authors like Berrada et al. (1996), Arthur and Ravidran (1981) and Puente et al. (2009) who propose the use of goal programming to solve the medical staff rostering problem. In their approach, a set of hard and soft constraints for scheduling emergency staff must be defined. Soft constraints are treated as goals whilst hard constraints must be satisfied in order to generate a feasible schedule that optimises the use of resource and satisfies the demand of a fixed planning horizon. To solve the goal programming formulations of medical staff rostering problem, some authors have proposed the predominant use of genetic algorithms ("GAs") (Puente et al., 2009).

In order to define goals, Puente et al. (2009) proposed the use of specialized methodologies like Delphi, to construct soft constraints for the models. Topaloglu (2006) used an analytic hierarchical process (AHP) to quantify the importance of each goal. In addition, multicriteria weighting has been used for the purpose of soft constraints development. From our review of the literature it appears that the use of tools for multi-criteria analysis is necessary in order to quantify the importance of constraints so that multi-objective programs can be developed.

A number of heuristic methods have been designed to resolve the nurse rostering problem. Among the heuristics, the most frequently used are "shuffling" and "greedy shuffling" algorithms. The former finds different schedules and then improves one by exchanging one element of this schedule with a part from another. The latter works by calculating all the shuffles for all personnel and sorting them by highest benefit. To develop cyclic schedules Marchionno (1987) presented a step-by-step guide to generate feasible schedules. Also Frances (1966), Mailer-Rothe and Wolfe (1973) and Anzai and Miura (1987), describe computerized programs for producing cyclic duty rosters.

In the same way as mathematical programming, heuristic approaches attempt to create a cyclic schedule for staff and then improve it by comparing results and introducing the preferences and requirements of the emergency department (ED). Smith and Wiggins (1977), proposed to divide the problem into multiple stages and then construct a detailed schedule subject to constraints found in the first stages of model.

In order to solve staff rostering problems, it is possible to see that metaheuristic and hybrid approaches have been particularly useful. The former has used mainly tabu search (TS) to generate feasible patterns and then improve them using different methods. Burke et al. (2001) described a memetic algorithm (MA) that incorporates TA into a GA which uses steepest descent trends for each individual. The results reported for the nurse rostering problem are better than those obtained using the hybrid TS approach previously devised by Burke et al. (1999). In the same way, Bellanti et al. (2004) presented a local search approach to solve nurse rostering problems. This approach was based on a neighborhood that works on partial solutions which are completed by a greedy procedure which avoids the generation of unfeasible solutions. Within this structure, a TS procedure and an iterated local search (ILS) procedure were proposed.

Regarding the hybrid approach, C.-C. Tsai and S. H.A. Li (2009), presented a two stage mathematical model in order to solve nurse rostering problems. Firstly, they looked to arrange nurse work and vacation schedules, then they used a GA to solve schedules while checking violation of government regulations, hospital management requirements, and scheduling fairness. The second stage saw the adoption of a GA approach to arrange the nurse rosters and solve the question of optimal schedules. E. K. Burke et al. (2008) presented a hybrid heuristic ordering with variable neighbourhood search (VNS). In their paper they showed that the search can be extended in order to improve solution quality by repeated use of heuristic ordering, variable neighbourhood search and back-tracking.

This paper tackles the problem of estimating the optimal number of specialized workers needed in a hospital and the optimal assignation of physicians and nurses to shifts taking into account particular constraints. Once the staff number is calculated, their schedule is fixed according to a large number of legal and institutional limitations. In order to accomplish all these goals, three main levels have been identified in respect of this problem; they represent short, medium and long term decisions.

We focus on solving strategic and tactical level problems; this is medium and long term decisions, by proposing two linear models. The first solves the problem at a strategic level and estimates the staff number required in a year. The second, which addresses matters at a tactical level, takes, as a parameter, the solution of the first model and assigns to each shift and each task, the required staff according to the large number of aforementioned legal and institutional constraints. Next section presents the proposed mathematical model to solve these two problems. Between the previous projects and this work, there are some remarkable differences. First, the present work is centered in all type of nurses and physicians involved in the attention of a patient instead of an only position like most works do. In addition, this study is carried out in a health care center emergency area instead of its internal areas like others works due to the complexity that turns out of understanding the emergency area operation. Finally, this project integrates two different planning levels instead of focusing in a single one and giving by well-known the next or previous level. In the case of the personnel planning, there is