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Decision Support

A multi-criteria approach for hospital capacity analysis

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ABSTRACT

Hospitals are critical elements of health care systems and analyzing their capacity and productivity is a very important topic. To perform a system wide analysis of public hospital resources and capacity, a multi-objective optimization (MOO) approach has been proposed. This approach identifies the theoretical capacity of the entire hospital and facilitates a sensitivity analysis, for example of the patient case mix (PCM). It is necessary because the competition for hospital resources, for example between different patient types and hospital units, is highly influential on the hospitals productivity. The MOO approach has been extensively tested on a real life case study and significant worth is shown. In this MOO approach, the epsilon constraint method (ECM) has been utilized. However, for solving real life applications, with a large number of competing objectives, it was necessary to devise new and improved algorithms. In addition, to identify the best solution, a separable programming approach was developed. Multiple optimal solutions are also obtained via the iterative refinement and re-solution of the model.

1. Introduction

Hospitals are critical elements of the health care system. In recent years the demand for their services has increased greatly and in response they have become larger and more sophisticated. Access to hospitals and to health care services is very competitive worldwide. Public hospitals for instance are rarely constructed for specific services and typically must treat many different types of patients. There are a variety of different competitions that may be characterized. How this competition is regulated or otherwise decided, greatly affects the capacity of a hospital and the outcomes of any analysis of hospital capacity. This paper focusses upon that aspect and investigates whether a multi-objective capacity analysis (MOCA) can be used to identify the theoretical capacity of a hospital when there are competing capacity metrics. Theoretical capacity is an upper bound and describes the best possible performance of the hospital in terms of productivity. Public hospitals are the main focus of this work. Private hospitals however are equally relevant and have not been excluded. Given the increased pressures and challenges placed upon hospitals worldwide, this paper is believed timely.

There are many ways to regulate competition and a multi-objective approach is believed to be the best way to perform a sensitivity analysis of hospital capacity. That hypothesis is tested in this paper. The significance of a multi-objective approach is that a variety of competing capacity metrics can be incorporated. In contrast, an approach involving a single objective, for instance as the total number of patient cases, with for example no emphasis or meaning given to patients or services of different type, is avoided. As few if any hospital operates with a single patient type or service, and those patients are not of equivalent worth, our approach is evidently superior.

The format of this paper is as follows. In Section 2 a brief review of the literature is presented. In Section 3 the multi-objective framework is introduced and appropriate solution techniques are then developed in Section 4. A numerical investigation has been provided in Section 5 and demonstrates the application of the proposed MOCA to real life. A summary of this articles contributions and the conclusions are provided in Section 6.

2. Literature review

In this section, research concerning hospital planning is first discussed, and then approaches for performing multi-objective optimization are reviewed.

2.1. Hospital planning

Our review of the literature indicates that approaches for identifying hospital capacity from a multi-objective viewpoint are limited. In past research, a variety of different hospital capacity planning problems have been proposed. These differ greatly. Evidently there is no single "standard" hospital capacity planning problem. Those planning problems have been addressed in a variety of different ways as discussed in Rechel, Wright, Barlow, and McKee (2010). For example, some approaches have been

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purely analytical, and others have been empirical or simulation based. Recent articles that are noteable, insomuch as they are relevant to the focus of this paper, include Abdelaziz and Masmoudi (2012), Dellaert, Cayiroglu, and Jeunet (2015), Ma and Demeulemeester (2013), Vanberkel, Boucherie, Hans, and Hurink (2014). For example, Abdelaziz and Masmoudi (2012) developed a multi-objective stochastic mathematical programing model to determine what number of beds should be assigned to hospital departments in order to satisfy the random demand. In their bed capacity management approach, three objectives were considered, namely cost of creating a new bed, and the number of physicians and nurses working in each hospital. A recourse approach and a goal programming approach were used to transform the multi-objective stochastic program to a certainty equivalent program. Ma and Demeulemeester (2013) developed an integrated and iterative multi-level approach for hospital planning. Their approach consists of three phases. In the first phase (i.e. case mix planning) an optimal patient mix and volume are selected that brings the maximum profit. Then bed capacity is reallocated and a master surgery schedule is created. In the third phase simulation is performed to evaluate operational policies. Optimization models are developed to faciltate the first two phases. Vanberkel et al. (2014) considered how to choose patient case mixes in hospitals in order to achieve the greatest benefit, and to achieve a specified DRG mix. Hospital capacity and case mix decisions are jointly considered to facilitate joint decision making over a long term planning horizon. Hospitals are modelled as a queing system and an integer linear programming model was formulated. The model is solved using a time discretization and an approximate solution approach (i.e. a heuristic). Dellaert et al. (2015) considered the creation of tactical plans of elective patient surgeries and the utilization of hospital resources, in order to increase hospital efficiency. The tactical plan is a description of the number of patients in each category to be operated on for each day of the horizon. They developed methods to determine the operational performance of tactical plans in hospitals. For example, their method computes exact waiting time distributions for patients. To reduce waiting times, slack planning and smoothing have been proposed. Four resources were considered, namely operating theatres, beds and nurses in the ICU, and beds in a medium care unit. Hence this approach is not holistic and only focusses upon one part of the entire hospital system.

2.2. Multi-criteria optimization

The epsilon constraint method (ECM) is one of the most popular methods for solving multi-objective optimization problems (MOOP) and to generate the set of non-dominated solutions. In this article it is used as the basis of the techniques we have developed to perform our multi-objective hospital capacity analysis. In recent years, a number of articles have applied it to real life applications and have considered ways to improve it. Laumanns, Thiele, and Zitler (2006) developed an adaptive scheme to approximate the Pareto set. In their approach the m-1 dimensional hyper-grid is generated dynamically and is stored as a matrix of vectors. The set of searched regions and infeasible regions is updated as the search progresses. Ehrgott and Ruzika (2008) considered weaknesses of the epsilon constraint method. In response they introduced slack variables in the formulation and elasticized constraints. Mavrotas (2009) proposed several augmented versions to reduce redundant iterations, and to accelerate the search. The production of weakly optimal Pareto solutions is avoided in their approach. Berube, Gendreau, and Potvin (2009) applied an epsilon constraint method to a bi-objective traveling salesman problem. Özlen and Azizoğlu (2009) developed an algorithm to generate all non-dominated points for MIPs based on the epsilon constraint method. Their method identifies individual objective efficiency ranges. These are used to improve the search for non-dominated solutions. Aghaei, Amjady, and Shayanfar (2011) applied multi-objective techniques to an electricity market clearing problem. A lexicographic optimization and augmented epsilon constraint method was applied. That approach was compared with the traditional epsilon constraint method and found to be greatly superior. Kirklik and Sayin (2014) introduced an algorithm that involves a new partitioning mechanism. There is no limit on the number of objectives that can be handled by their approach, however they conclude that as the problem size increases the computational requirement are unrealistically high. Klamroth, Lacour, and Vanderpooten (2015) investigated how improved local upper bounds can be obtained for epsilon constraint like methods in order to improve the search for non-dominated solutions. Two incremental approaches were presented.

Other approaches for solving MOOP exist. For instance Lokman and Köksalan (2013) presented two algorithms for multi-objective integer programming. Their search procedure is an extension of a previous approach by Sylva and Crema (2007). They introduce binary variables and additional constraints to exclude regions dominated by previously generated points.

3. Multi-criteria hospital capacity analysis (MOHCA)

A multi-objective capacity analysis (MOCA) is presented here for hospitals (i.e. a MOHCA). This approach builds upon the research in Burdett and Kozan (2006, 2008), Kozan and Burdett (2005) and Burdett (2015). In those articles, optimization approaches have also been formulated, for the identification of theoretical capacity in several other domains. The underlying mathematical model that is used as the basis of our MOHCA is now reviewed.

3.1. The hospital capacity model (HCM)

This section's HCM is a mixed integer linear programming formulation (MILP). This model is holistic as it includes the main hospital elements, such as the recovery wards, operating theatres, intensive care units, and the emergency department. The model's purpose is to determine the maximum number of patient treatments that can be performed over a specified period of time T, subject to a variety of technical constraints. The solution of this model provides a plan that describes how the hospital's resources are used. The plan specifies the number of patients that can be processed of each type $\gamma \in \Gamma$. It also determines where those patients are treated within the hospital. In other words, it describes all resource assignments and resource utilisations.

To apply the HCM, detailed information concerning the types of activities $\phi \in \Phi$ and their respective processing times are required for different patient types $\gamma \in \Gamma$. Every patient that visits the hospital receives some type of treatment or care or else participates in some type of diagnostic or assessment activity. These activities all utilize hospital capacity and are performed by hospital units. Each hospital unit $u \in U$ is associated with a particular medical or surgical specialty $s \in S$. For patients of type γ, a variety of patient care plan (PCP) eventuate. They are denoted by Ψ_γ. Each PCP $\psi \in \Psi_\gamma$ is defined in the following way: $PCP = \{(\phi, u, t, r) | \phi \in \Phi, u \in U, t \in \mathbb{R}\}$. Each tuple (ϕ, u, t, r) describes the activity type, the hospital unit performing the activity, the time to perform the activity, and the set of resources required. A PCP task is denoted by $o_{\gamma,\psi,k}$ and the activity, unit, and time required are denoted by $\phi_{\gamma,\psi,k}, u_{\gamma,\psi,k}, t_{\gamma,\psi,k}$. The set of treatment areas and spaces are denoted by $w \in W$ and $\pi \in \Pi$ respectively. Unit-activity tuples (u, ϕ) are used to describe the places (i.e. areas) where the activity can be performed. It is assumed that each hospital unit