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A hybrid genetic algorithm-queuing multi-compartment model for optimizing inpatient bed occupancy and associated costs

Smaranda Belciug [a], Florin Gorunescu [b,*]

[a] Department of Computer Science, University of Craiova, Craiova 200585, Romania
[b] Department of Biostatistics and Informatics, University of Medicine and Pharmacy of Craiova, Craiova 200349, Romania

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ABSTRACT

Purpose: Explore how efficient intelligent decision support systems, both easily understandable and straightforwardly implemented, can help modern hospital managers to optimize both bed occupancy and utilization costs.
Methods and materials: This paper proposes a hybrid genetic algorithm-queuing multi-compartment model for the patient flow in hospitals. A finite capacity queuing model with phase-type service distribution is combined with a compartmental model, and an associated cost model is set up. An evolutionary-based approach is used for enhancing the ability to optimize both bed management and associated costs. In addition, a "What-if analysis" shows how changing the model parameters could improve performance while controlling costs. The study uses bed-occupancy data collected at the Department of Geriatric Medicine – St. George's Hospital, London, period 1969–1984, and January 2000.
Results: The hybrid model revealed that a bed-occupancy exceeding 91%, implying a patient rejection rate around 1.1%, can be carried out with 159 beds plus 8 unstaffed beds. The same holding and penalty costs, but significantly different bed allocations (156 vs. 184 staffed beds, and 8 vs. 9 unstaffed beds, respectively) will result in significantly different costs (£755 vs. £1172). Moreover, once the arrival rate exceeds 7 patient/day, the costs associated to the finite capacity system become significantly smaller than those associated to an Erlang B queuing model (£134 vs. £947).
Conclusion: Encoding the whole information provided by both the queuing system and the cost model through chromosomes, the genetic algorithm represents an efficient tool in optimizing the bed allocation and associated costs. The methodology can be extended to different medical departments with minor modifications in structure and parameterization.

1. Introduction

The problem of how to allocate healthcare resources has become increasingly pressing today. One of the major issues is the cost of the healthcare system in relation to its efficiency. The natural limitation of the allocated resources leads to the need for better management. Without an efficient management, the healthcare system will not be able to offer high quality patient care with affordable costs. One of the means to achieve a better management of the clinical facilities is the appropriate use of beds. This is directly connected to the patient flow through hospital, based on the progression of the health status. There are currently published data regarding this issue, Eurostat/European Commission – "Health care facilities" presenting an updated description of the hospital beds situation throughout the European Union [1] http://ec.europa.eu/eurostat/cache/metadata/Annexes/hlth_res_esms_an9.pdf [accessed 19.10.15]. A key solution for the effective management of healthcare resources is the optimization of bed occupancy and associated costs.

Queuing theory, particularly, is widely used in making decisions to improve the customer service in various fields, including healthcare. The rich literatures regarding the contributions and applications of queuing theory in healthcare, along with useful information to model a healthcare process, have been recently reviewed in [2]. Finite-capacity queuing systems are often used in healthcare. In [3], the authors study a queuing system with finite-capacity buffer and a two-phase Cox distribution for service. The

* Corresponding author at: Department of Biostatistics and Informatics, University of Medicine and Pharmacy of Craiova, 2 Petru Rares Str., Craiova 200349, Romania. Tel.: +40 727 827 833; fax: +40 251 412 673.
E-mail addresses: smaranda.belciug@inf.ucv.ro (S. Belciug), florin.gorunescu@webmail.umfcv.ro, gorunef@gmail.com, fgorun@rdslink.ro (F. Gorunescu).

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proposed methodology is applied to optimize a geriatric care unit by using an empirical analysis of the model and numerical calculations. Because queuing systems allow the use of simulation models for planning bed inventory in hospitals, the authors of [4] developed a simulation model, based on queuing theory, used for planning the bed capacity. A queuing model is applied in [5] to improve the quality of healthcare service. The authors propose a $M/E_k/c$ system to model an orthopedic ward service aiming to determine both the optimal number of beds and the average loss of revenue across different wards. A queuing network with different priority classes of customers was used for Emergency Departments [6]. The authors propose a continuous-time Markov chain to analyze several hospital systems in order to assess the impact of systems resources on offload delays.

Inspired by the compartmental kinetics, the patient flow may be described as the behavior of a drug in the body. Compartmental models have previously been shown to provide a suitable description of the patient flow through a hospital department. Starting with a deterministic two-compartment mathematical model [7], they went on to make further progress when stochastic models, along with mixed exponential distributions, were proposed [8,9].

Previous work [10,11] has introduced two queuing models ($M/PH/c$ and $M/PH/c/N$) in order to optimize the use of hospital resources. They enable the estimation of the probability of lost demands and the mean number of patients in hospital. Both approaches face a trade-off between the costs of empty beds and the cost of turning patients away, solved by introducing a cost function. The direct estimation of several values regarding the rejection probability and the associated cost, computed for different parameter settings, has been used for the optimization purpose. For the sake of simplicity, since the rejection probability and the associated cost are multivariable functions, their evaluation has been based on approximate computation (rejection probability), and graphical estimation (cost function). The former has been computed by varying only one parameter at a time, while a two-dimensional graph representing indifference curves has been used for the latter. Moderate accuracy has been a direct consequence of this approximation methodology. To overcome this empirical computation, the current work proposes a flexible strategy for the optimization of hospital bed occupancy and associated costs, based on the evolutionary paradigm. The mathematical model for the patient flow has been developed by combining elements of queuing theory with results from compartmental models in conjunction with phase-type distributions. An associated cost model has been set up in order to balance the expenses related to refusing patients and with maintaining the necessary number of beds. The methodology used in this paper is a modeling/simulation process in two steps. The first one consists in formalizing the flow of patients and associated costs. The former is modeled by means of both a finite capacity queuing model and a compartmental model, while the latter is achieved by using a base-stock policy approach [12]. The second one, based on the use of a genetic algorithm (GA), enables the exploitation of this formalization to optimize both the inpatient bed occupancy and associated costs. The work has two objectives. Firstly, we estimated the optimal values of the parameters defining the background queuing model in order to achieve a probability of a patient being turned away of no more than a pre-specified threshold. Secondly, we estimated the optimal values of the bed inventory and of the penalty and holding costs in order to minimize the long-run average associated cost. In addition, a "What-if analysis" has also been performed to highlight how changing the model parameters could improve performance while controlling costs. The achievement of these goals provides the hospital managers with a flexible and effective tool to simulate different possible scenarios, allowing them to improve and optimize the management of their unit. Different from the existing papers in literature, our approach uses the evolutionary paradigm in order to optimize both bed allocation and associated costs. It takes into account the diverse nature of the model parameters (both discrete and continuous), and considers the main system outcomes (rejection probability and associated costs) as objective functions. To our knowledge, no such approach has been used so far for bed and costs management in finite capacity queuing systems.

2. Materials and methods

The problem we wish to deal with in this paper is the optimization of the patient throughput in clinical departments and of the associated costs. It takes into account the use of some specific measurements, such as arrival rate, average length of stay, bed inventory, size of a possible waiting room, holding costs, etc. The components of the active healthcare service, such as short-term care, medium-term care, long-stay care, etc., depending on the clinical services provided by the hospital department, imply periods of time and resources. To deal with this complex problem, we converted the pattern of bed occupancy into the flow of patients through the clinical system. At the beginning, all patients are admitted into the hospital. It is noteworthy that they are not 'homogeneous', usually belonging to different categories. One group requires acute care, while others require medium or long-term rehabilitation. Accordingly, from acute care, they are either discharged back to community, or are transferred to the medium/long term care, from where they are discharged back or stay until death. We approached this system by means of queuing techniques, considering a compartmental model associated to different states (short-stay, medium-stay, etc.), and a mixed exponential distribution describing the average length of stay. The optimization of bed occupancy and associated costs, involving finding the optimal balance between bed inventory, holding costs and penalty costs, was addressed by the use of GAs.

2.1. Compartment model for hospital patient flow

Since a modern hospital/clinical department represents a complex system, we need to identify patterns within this complexity. Although there are a wide variety of patients with different diseases (e.g., geriatrics, surgical, stroke, etc.), the general context is similar enough, enabling the hope for a common approach regarding the flow.

Inspired by pharmacokinetics, which currently uses the multi-compartment model, the hospital/clinical department might be considered as a 'body' with different 'organs' (compartments). The number of transient patients thus represents the amount of drug [13]. Different from pharmacokinetics, where the tracking of an individual molecule of drug is measured by the total concentration of the drug in the organ, in the case of patient flow one can use the distribution of the patient length of stay.

While a one-compartment model assumes a similar treatment for all patients (e.g., acute care), two- and three-compartment models assume two and three different kinds of treatments (e.g., acute care and long-term rehabilitation). It is worth mentioning that there are situations better described by more than three compartments [8,14,15].

The mathematics behind the two-compartment model [13] can be briefly described as follows. Assume the clinical department has a constant admission rate A in equilibrium state, and let $N_i(s)$, $i = 1, 2$ be the number of patients in each compartment (A and B) with length of occupancy s (days). Let r_1 and r_2 be the rates of discharge from compartment A and B respectively, with the assumption that $r_2 < r_1$; let ν_1 be the rate of transfer from A to B. The model is