Simulation and Optimization Methods Applied to Outpatient Health Center Operations

Dissertation Manuscript

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August 2018

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Abstract

In recent years, demand for ambulatory care services in the United States has steadily increased, particularly in comparison to demand for hospital inpatient services. In order to respond to the growth in demand for ambulatory care service, there is a need for providing effective care while improving the efficiencies of health care operations. Efforts to increase efficiency in ambulatory care can include changes to day-to-day operations of an outpatient clinic such as exam room allocation policies, or one-time large scale changes such as outpatient clinic layout design. Additionally, efficiencies can be achieved by adjusting practices and decision making in multiple clinics at the same time, particularly accounting for the interdependencies that exist among multiple outpatient clinics within a health center. In this dissertation, we show that how increasing flexibility or resource sharing, and managing the clinic interdependencies can increase the efficiency of the clinics and correspondingly provide better timeliness of care.

Particularly, in the first chapter, flexibility in exam room allocation policies in outpatient clinics are analyzed using a discrete-event simulation model. Rather than dedicating exam rooms to physicians, or pooling all rooms among all providers, we characterize the impact of alternate policies that partially share exam rooms among providers. Our findings show that it is not necessary to fully share rooms among providers in order to reduce patient LOS and physician idle time. Instead, most of the benefit of pooling can be achieved by implementation of a compromise room allocation approach, limiting the need for significant organizational changes within the clinic.

In the second chapter, efficiency of patient care that is impacted by physical layout decisions is examined. Particularly, relationships between physical layout designs, flexible patient flows, and operational policies are analyzed through development of a simulation optimization framework. For this purpose, the outpatient clinic layout problem is modelled as a Mixed Integer Linear Programming (MILP) and solved with a meta-heuristic algorithm accounting for the size of the problem. Then a discrete-event simulation is used to evaluate the candidate layouts accounting for stochastic patient flows. Our findings show the importance of physical design on workflow for providers and flow of patients in the design of new ambulatory care clinics.

In the third chapter, the impact of managing existing interdependencies among different health centers are characterized. Operation of the radiology department can potentially impact several

other outpatient clinics such as rheumatology, orthopedics, primary care, and surgery. In order to manage such interdependencies, a simulation optimization framework is proposed.

Chapter 1: New Flexible Room Allocation Policies in Outpatient Clinics[1]

Abstract

To address prolonged lengths of stay (LOS) in ambulatory care clinics, we analyze the impact of implementing flexible and dynamic policies for assigning exam rooms to providers. In contrast to the traditional approaches of assigning specific rooms to each provider or pooling rooms among all practitioners, we characterize the impact of alternate compromise policies that have not been explored in previous studies. Since ambulatory care patients may encounter multiple different providers in a single visit, room allocation can be determined separately for each encounter accordingly. For the first phase of the visit, conducted by the medical assistant, we define a dynamic room allocation policy that adjusts room assignments based on the current state of the clinic. For the second phase of the visit, conducted by physicians, we define a series of room sharing policies which vary based on two dimensions, the number of shared rooms and the number of physicians sharing each room. Using a discrete event simulation model of an outpatient cardiovascular clinic, we analyze the benefits and costs associated with the proposed room allocation policies. Our findings show that it is not necessary to fully share rooms among providers in order to reduce patient LOS and physician idle time. Instead, most of the benefit of pooling can be achieved by implementation of a compromise room allocation approach, limiting the need for significant organizational changes within the clinic. Also, in order to achieve most of the benefits of room allocation policies, it is necessary to increase flexibility in the two dimensions simultaneously. These findings are shown to be consistent in settings with alternate patient scheduling and distinctions between physicians.

Problem Overview

One of the driving factors, in timeliness of care within ambulatory care settings is the efficiency with which resources are deployed. Much of the research related to health care efficiency and resource utilization in outpatient clinics, or ambulatory care settings, examine the impact of changes to variable resources, such as physicians and nurses, which can be adjusted to match

[1] Vahdat, Vahab, Jacqueline Griffin, and James E. Stahl. "Decreasing patient length of stay via new flexible exam room allocation policies in ambulatory care clinics." Health Care Management Science (2017): 1-25. (link)

changing needs(Cayirli and Veral 2003, Harper and Gamlin 2003, Kaandorp and Koole 2007, Patrick 2012, Guler 2013, Lee, Min et al. 2013, Hahn-Goldberg, Carter et al. 2014). This focus on variable resources overlooks the important role of the management of fixed resources, such as exam rooms, in the delivery of outpatient care. In fact, one common problem in healthcare organizations is the simultaneous underutilization of physical, or fixed, resources paired with poor quality of patient care. For example, in some outpatient clinics exam rooms are used less than half of the time the clinic is open while, at the same time, the average patient wait time in the waiting area is high (Berg, Denton et al. 2010, Haraldsson 2014, Overmoyer, Kadish et al. 2014).

Much of the research examining the allocation of physical resources in healthcare primarily address the assignment of specialized rooms such as operating theaters (Cardoen, Demeulemeester et al. 2010, Hulshof, Boucherie et al. 2013, Hosseini and Taaffe 2015, van Veen-Berkx, Elkhuizen et al. 2016), intensive care units (Shortell, Zimmerman et al. 1994, Seung-Chul and Ira 2000, Lin, Chaboyer et al. 2009), and critical care units (Sinuff, Kahnamoui et al. 2004, Marmor, Rohleder et al. 2013). A limited number of researchers examine the allocation of identical, generally equipped exam rooms in outpatient clinics. With a focus on generally equipped rooms, which are most prevalent in ambulatory care clinics, we develop a discrete event simulation (DES) model of an outpatient clinic to examine how new strategies for managing these resources can drive improvements in quality of care. Specifically, we examine the role of exam room assignment policies and the benefit that flexibility of resources can contribute to patient wait times and lengths of stay.

While multiple strategies exist for assigning physicians to rooms, primarily one of two approaches are used in ambulatory care settings: (i) dedicated assignment and (ii) sharing, or pooling, of rooms. In the majority of clinics, each room is assigned to a specific provider for an entire session, referred to as a “dedicated” room allocation policy(Cote 1999). Correspondingly, each patient is only visited in a room designated to his or her physician. One disadvantage of such a policy is that room availability may be a bottleneck, leading to longer wait times for the initiation of a patient’s visit. The greatest advantage of using a dedicated room allocation policy is the ease of implementation and consistency in patient and physician flows throughout the day.

Alternatively, in a “pooled” room allocation policy, all rooms are shared among all of the practicing physicians. In this policy, patients may be visited in any available room. Previous research has demonstrated that this policy can increase room utilization(Haraldsson 2014, Norouzzadeh, Riebling et al. 2015) and decrease patient wait times(Santibanez, Chow et al. 2009) with some limitations. In some clinics, the pooling of rooms causes longer walking distances for physicians due to the design of the space and is perceived not to be practical (Norouzzadeh, Riebling et al. 2015). Another disadvantage of this policy is that unexpected increases in visit length by one provider or patient may directly influence other physicians and patients. Additionally, complicated patient flows may cause extra workload for clinic staff and providers. Similar effects occur in call centers in which pooling resources leads to increased variability which correspondingly offsets any gained efficiencies (Dijk and Sluis 2008).

In order to achieve advantages of both dedicated and pooled room allocation policies, we evaluate the use of “hybrid” room allocation policies, which allow for the system to achieve a middle ground between dedicated and pooled policies. We demonstrate how increased flexibility in room assignment policies can contribute to better overall patient quality of care, while imposing minimal changes to the status quo dedicated policies.

We distinguish the room assignment policies corresponding to the two phases of patient-provider interaction, as occurs in most outpatient clinics. The first phase of care for a patient is the completion of intake questions, tests, and measurements by a Nurse Practitioner (NP) or Medical Assistant (MA). In the second phase of care, the patient is visited by his or her physician (MD). Often the patient will wait in an exam room between these two stages. Alternatively, in some clinics, such as ophthalmic centers, patients have a sequence of multiple visits and return to the waiting area after each phase of the visit, rather than remaining in one room(Pan, Zhang et al. 2015). Most commonly, room assignment decisions for the MA-patient and MD-patient visit phases are not distinct and are assumed to be the same. As we demonstrate, new paradigms for increasing flexibility in room assignments in either, or both, the MA-patient and the MD-patient phases can significantly improve not only the patient experience, through decreases in WT and LOS, but also physicians’ experiences, through reduced delays for initiating patient visits and reduced overtime.

The first chapter of the dissertation focuses on the study of a cardiovascular outpatient clinic in a major teaching hospital. While the results correspond to this institution, the value of exploring new strategies for utilizing limited exam rooms and increasing flexibility in room assignments can be extrapolated to other ambulatory care clinics. Specifically, the generalizable contributions of this work include:

- A new focus on and study of flexibility in room assignments for crowded ambulatory care settings, which allows for gaining much of the benefits of pooling resources while limiting the operational challenges that can occur with such a strategy. Benefits and barriers to implementation of this flexibility are investigated, accounting for multiple stakeholder perspectives.
- The distinct modeling of exam room allocation policies for two phases of patient care, specifically the MA-patient and MD-patient visits, allowing for analysis of the individual contributions of such policies and the cumulative benefit of joint deployment. The definition and analysis of two different strategies, or policy structures, for increasing flexibility in room assignments.
- When considering the MA-patient phase of the visit, we examine adaptive policies in which decisions for assigning rooms evolve based on the current state of the system.
- When considering the MD-patient phase of the visit, while assuming that room assignments remain fixed over time, we examine the relative benefits of changing two features of room sharing, the number of rooms being shared and the number of physicians sharing each of the rooms.
- The demonstration that most of the benefit of pooling can be achieved by implementation of a compromise room allocation approach, limiting the need for significant organizational changes within the clinic. These compromise approaches are most beneficial when changes are made to both features of room sharing.

Chapter 2: Outpatient Clinic Layout Design using Hybrid Simulation Optimization[2]

Abstract

While it is known that there is a strong relationship between form and function, often the impact of physical design on workflow can be overlooked in the design of new buildings and spaces. Correspondingly, further research is needed to examine how the efficiency of patient care is impacted by physical layout decisions. With the development of new models, relationships between physical layout designs, flexible patient flows, and operational policies are analyzed through development of a discrete event simulation approach.

Problem Overview

Among developed countries, the United States has the highest annual per-capita health expenditures, yet there are significant challenges to increase effectiveness and efficiency in the delivery of care. These challenges in improving care are a result of numerous design and operational decisions. These include long-term strategic level decisions, tactical medium-term planning decisions, and short-term operational decisions. Facility location, layout, and design are all examples of strategic decisions that have been studied in the healthcare sector. For example, new studies drive hospital design modernization of functionality and flexibility to evolve with technologies (Holst 2015). Hospital layout researchers aim to minimize travelling distances or associated costs of locating clinical and operational units inside hospitals (Amaral 2012, Arnolds and Nickel 2015, Helber, Böhme et al. 2016). While the designs and layouts of hospitals are optimized by minimizing the distances between units, this disregards the integration of the design with functionality such that the layout is efficiently designed for stochastic patient flow. For this purpose, a simulation-optimization model is used to design a healthcare center layout by considering such joint decisions that not only optimize the walking distances but also seek to optimize patient flow and resource utilization.

While traditional optimization methods are unable to solve large-scale layout problems, many researchers apply heuristics and meta-heuristics as promising algorithms to obtain near optimal

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[2] **A portion of this section is previously published as:**
Vahdatzad, Vahab, and Jacqueline Griffin. "Outpatient clinic layout design accounting for flexible policies." Proceedings of the 2016 Winter Simulation Conference. IEEE Press, 2016. (link)

solutions. Examples are Tabu Search(Liang and Chao 2008, Samarghandi and Eshghi 2010, Scholz, Jaehn et al. 2010), Simulated Annealing(Chwif, Barretto et al. 1998, Tasadduq, Imam et al. 2015), and Genetic Algorithms(Al-Hakim 2000, Azadivar and Wang 2000, El-Baz 2004, Sadrzadeh 2012). This research expands on the state-of-the-art literature of layout optimization by introducing a simulation-optimization framework that simultaneously find solutions to a large scale combinatorial optimization problem by a metaheuristic algorithm and evaluates the complex outpatient clinic layout with a discrete event simulation model.

The proposed simulation-optimization approach has three phases. The simulation model is used in phase 1 to determine stochastic patient and provider flows from an outpatient clinic case study, a children orthopedics clinic located in New England, USA. Outputs of the simulation model, specifically approximation of flows between units, is then used as an input parameter of phase 2, a Mixed-Integer Linear Programing (MILP) representation of the layout optimization problem. Particle Swam Optimization (PSO), is used to solve the optimization model. Due to the size of the problem, PSO is unable to find good solutions. Hence, a decomposition approach is used where in the first stage pods that include four smaller units are located in the layout. In the second stage, each pod is decomposed and relatively enlarged to find the best layout for the units inside the pod. The solution procedure is repeated several times to find the best distinct layouts consisting of relative locations and shapes for all units in the given planar space. In phase 3 of the simulation-optimization, candidates' layouts are compared using discrete-event simulation to find the best layout with regard to performance metrics such as minimizing maximum patient and physician walking distances.

Chapter 3: using simulation optimization for Interdependent operations in health centers[3]

Abstract

Many patients require multiple services provided by different departments and facilities during one visit to a health center or hospital. These multiple services provided to common patients define interdependencies among departments within a hospital, in which the operation and efficiency of one department may impact the other interrelated departments. In order to minimize the total patient length of stay for those with multiple services, a simulation-optimization framework is constructed. The day-to-day operations of each department is simulated using discrete-event simulation modeling. At the beginning of each iteration, an optimization model for each node defines the patient and provider schedules and resource allocation for each hour of the day. The simulation results, inflows, and outflows of each department are used to inform the next iteration of the optimization model. This iterative procedure continues, until the performance gap is minimal.

Problem overview

Although existing literature advocates the need for outpatient clinics, inpatient wards, and Emergency Rooms (ER) to increase efficiency and quality of care, there is a dearth of studies analyzing aggregate efficiency of two or more health center units when there exist interdependent operations among the departments. Most research focuses on a specific clinic or a department in a hospital and seeks to optimize the performance of that unit accordingly. But many patients need to visit two or more hospital departments in one visit, such that even if each department is locally efficient, that does not guarantee that patients will experience timely care when they are required to visit multiple departments. On the other hand, inefficiency in one department can cause the interrelated departments to experience inefficiencies, as a result of these interdependencies. The

[3]**A portion of this section is previously published as:**
Vahdat, V., and J. Griffin. 2017. "Proactive Patient Flow Redesign for Integration of Multiple Outpatient Clinics". *Accepted for publication* In Proceedings of the 2017 Winter Simulation Conference, Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc
Vahdat, V., J. Griffin, S. Burns, and R. Azghandi. 2017. "Using Simulation Optimization for Interdependent Operations in Health Centers". *Accepted for publication* In Proceedings of the 2017 Winter Simulation Conference, Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc

integrated patient length of stay, the difference between the arrival and departure of the patient from the hospital, is often overlooked by department managers, either because of a lack of information sharing between the departments or a failure to understand the importance of unified decision-making among departments which can maximize overall patient quality of care.

Interdependencies in hospital operations can be characterized by the scope and the type of the dependency. While the scope of interdependencies refers to the number of departments that are interconnected, the type refers to the nature of the relationship that causes interdependency between two or more departments. The first type of interdependency can be defined as a one-to-one (1:1) relationship, where one department has interdependent operations with another department in the hospital and the interdependency can be bi-directional. One example of this type of interdependency is an obstetric outpatient clinic with a labor and delivery inpatient ward. Patients of the outpatient clinic are expected to go to the inpatient ward for delivery within a certain timeframe. Hence, the outpatient clinic patient volume and the rate of new patients to the clinic is expected to directly affect the demands on the inpatient labor and delivery unit months later. Additionally, the patient volume in the labor and delivery department will directly affect the patient volume for postpartum services in the obstetrics department.

The second type of interdependency can be defined as a one-to-many relationship (1:N), meaning that one department is interconnected with multiple other departments, but the relationship is not necessarily bi-directional. An example of the one-to-many interdependency relationship is the Emergency Room (ER) with inpatient units of a hospital. The complexity of ER operations is due, in part, to the extensive variety of types of patients that are seen, both with regard to the type of injury and the severity of the ailment. Patients in the ER can be subsequently admitted to many different departments of a hospital including operating rooms, imaging services, or inpatient units. Correspondingly, the operation of the ER, whether efficient or inefficient, directly effects many departments within the hospital and these destination departments need to plan accordingly. Another example of a one-to-many interdependency is the operation of medical interpreter groups within a hospital. Interpreters scheduling is very complex due to being based on the variety of languages provided and uncertainty regarding demands among different departments. Correspondingly, a delay in the availability of interpreters can lead to significant delays in many departments throughout the hospital that are waiting for these services.

The third type of interdependency is defined as a many-to-one relationship (N:1) where many departments require services from one department and where the relation is not bi-directional. For example, the radiology and imaging department often operates as a critical hub, where patients from many different departments of a hospital visit to obtain required imaging services as part of the treatment process. Patients from many different specialties, including primary care, surgery, orthopedics, and rheumatology need imaging services before, in the middle of, or after their visit. Hence, the efficiency of the radiology department's operations impact several outpatient and inpatient departments.

The complexity of patient flows and uncertainty of processes within single clinics often supports the need to study these systems with the use of discrete-event simulation (DES) models. While this DES method can be used to show the day-to-day operations of each department, simulation per se cannot optimize shared decisions that impact interdependent departments. Hence, a simulation-optimization algorithm is proposed to address the three types of interdependency defined above. The general framework for the proposed solution is as follows. A network model is constructed in which nodes correspond to the departments and the edges represent interdependencies among nodes. Note that edges can be uni-directional or bi-directional, depending on the type of interdependency, and there may be outflows or inflows to each node. At each node, a simulation model is constructed that corresponds to detailed processes within each department.

To minimize integrated patient length of stay, certain decision variables are optimized at the beginning of each iteration in each node. These decision variables include patient and physician scheduling and resource allocation. The simulation model at each node uses optimized decision variables as input parameters and runs for a specified time frame. The outputs of the simulation model for each unit are used as performance metrics of the proposed solution. Additionally, information pertaining to outflows and inflows from each node at each hour of the day are used as inputs to the next optimization model iteration. The optimization model is again used to find the value of decision variables in each node based on the information from the simulation model. This iteration process continues until either the improvement gap becomes very small or a predefined timeframe is reached. The simulation-optimization framework can be adjusted to address the three types of interdependencies defined above.

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