DOCTORAL THESIS

Understanding the performance of healthcare services: a data-driven complex systems modeling approach

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Abstract

Healthcare is of critical importance in maintaining people's health and wellness. It has attracted policy makers, researchers, and practitioners around the world to find better ways to improve the performance of healthcare services. One of the key indicators for assessing that performance is to show how accessible and timely the services will be to specific groups of people in distinct geographic locations and in different seasons, which is commonly reflected in the so-called wait times of services. Wait times involve multiple related impact factors, called predictors, such as demographic characteristics, service capacities, and human behaviors. Some impact factors, especially individuals' behaviors, may have mutual interactions, which can lead to tempo-spatial patterns in wait times at a systems level. The goal of this thesis is to gain a systematic understanding of healthcare services by investigating the causes and corresponding dynamics of wait times.

This thesis presents a *data-driven complex systems modeling approach* to investigating the causes of tempo-spatial patterns in wait times from a self-organizing perspective. As the predictors of wait times may have direct, indirect, and/or moderating effects, referred to as complex effects, a *Structural Equation Modeling (SEM)-based analysis* method is proposed to discover the complex effects from aggregated data. Existing regression-based analysis techniques are only able to reveal pairwise relationships between observed variables, whereas this method allows us to explore the complex effects of observed and/or unobserved (latent) predictors on wait times simultaneously.

This thesis then considers how to estimate the variations in wait times with

respect to changes in specific predictors and their revealed complex effects. An *integrated projection* method using the *SEM-based analysis*, *projection*, and a *queuing model analysis* is developed. Unlike existing studies that either make projections based primarily on pairwise relationships between variables, or queuing model-based discrete event simulations, the proposed method enables us to make a more comprehensive estimate by taking into account the complex effects exerted by multiple observed and latent predictors, and thus gain insights into the variations in the estimated wait times over time.

This thesis further presents a method for *designing and evaluating service management strategies* to improve wait times, which are determined by service management behaviors. Our proposed strategy for allocating time blocks in operating rooms (ORs) incorporates historical feedback information about ORs and can adapt to the unpredictable changes in patient arrivals and hence shorten wait times. Existing time block allocations are somewhat ad hoc and are based primarily on the allocations in previous years, and thus result in inefficient use of service resources.

Finally, this thesis proposes a *behavior-based autonomy-oriented modeling* method for modeling and characterizing the emergent tempo-spatial patterns at a systems level by taking into account the underlying individuals' behaviors with respect to various impact factors. This method uses multi-agent Autonomy-Oriented Computing (AOC), a computational modeling and problem-solving paradigm with a special focus on addressing the issues of self-organization and interactivity, to model heterogeneous individuals (entities), autonomous behaviors, and the mutual interactions between entities and certain impact factors. The proposed method therefore eliminates to a large extent the strong assumptions that are used to define the stochastic properties of patient arrivals and services in stochastic modeling methods (e.g., the queuing model and discrete event simulation), and those of fixed relationships between entities that are held by system dynamics methods. The method is also more practical than agent-based modeling (ABM) for discovering the underlying mechanisms for emergent patterns, as AOC provides a general principle for explicitly stating what fundamental behaviors of and interactions between entities should be modeled.

To demonstrate the effectiveness of the proposed systematic approach to understanding the dynamics and relevant patterns of wait times in specific healthcare service systems, we conduct a series of studies focusing on the cardiac care services in Ontario, Canada. Based on aggregated data that describe the services from 2004 to 2007, we use the SEM-based analysis method to (1) investigate the direct and moderating effects that specific demand factors, in terms of certain geodemographic profiles, exert on patient arrivals, which indirectly affect wait times; and (2) examine the effects of these factors (e.g., patient arrivals, physician supply, OR capacity, and wait times) on the wait times in subsequent units in a hospital. We present the effectiveness of integrated projection in estimating the regional changes in service utilization and wait times in cardiac surgery services in 2010-2011. We propose an adaptive OR time block allocation strategy and evaluate its performance based on a queuing model derived from the general perioperative practice. Finally, we demonstrate how to use the behavior-based autonomy-oriented modeling method to model and simulate the cardiac care system. We find that patients' hospital selection behavior, hospitals' service adjusting behavior, and their interactions via wait times may account for the emergent tempo-spatial patterns that are observed in the real-world cardiac care system.

In summary, this thesis emphasizes the development of a data-driven complex systems modeling approach for understanding wait time dynamics in a healthcare service system. This approach will provide policy makers, researchers, and practitioners with a practically useful method for estimating the changes in wait times in various "what-if" scenarios, and will support the design and evaluation of resource allocation strategies for better wait times management. By addressing the problem of characterizing emergent tempo-spatial wait time patterns in the cardiac care system from a self-organizing perspective, we have provided a potentially effective means for investigating various self-organized patterns in complex healthcare systems.

Keywords: Complex Healthcare Service Systems, Wait Times, Data-Driven Complex Systems Modeling, Autonomy-Oriented Computing (AOC), Cardiac Care

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Abbreviations

ABM	Agent-based modeling
AOC	Autonomy-Oriented Computing
AOC-CSS	AOC-based cardiac surgery service
CCN	Cardiac Care Network of Ontario
CS-OR	Cardiac surgery operating room
CU	Catheterization unit
GP	General practitioner
HHSC	Hamilton Health Science Centre
LHIN	Local Health Integration Network
KL	Kullback-Leibler
LV	Latent variable
MSMQ-EC	Multi-server multi-queue with an entrance control queuing model
MV	Measurement variable
NE	North East
OPHRDC	Ontario Physician Human Resources Data Center
OR	Operating room
PCA	Principle component analysis
PLS	Partial least squares
RI	Recent immigrant
SEM	Structural Equation Modeling
SU	Cardiac surgery unit
TC	Toronto Central

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