

DOCTORAL THESIS

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

Tao, Li

Date of Award:
2014

[Link to publication](#)

General rights

Copyright and intellectual property rights for the publications made accessible in HKBU Scholars are retained by the authors and/or other copyright owners. In addition to the restrictions prescribed by the Copyright Ordinance of Hong Kong, all users and readers must also observe the following terms of use:

- Users may download and print one copy of any publication from HKBU Scholars for the purpose of private study or research
- Users cannot further distribute the material or use it for any profit-making activity or commercial gain
- To share publications in HKBU Scholars with others, users are welcome to freely distribute the permanent URL assigned to the publication

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

Acknowledgements

First of all, there are no words to express the deepest gratitude I have to my principal supervisor, Prof. Jiming Liu. Throughout the past rewarding four years, I have deeply appreciated his guidance, support, patience, and encouragement. His enthusiasm for meaningful researches, serious attitude, excelsior spirit, profound knowledge, and efficient working method, will be beneficial to me throughout my life.

I wish to thank my co-supervisor, Dr. Li Chen, as well as Dr. Bo Xiao, Prof. Ho Cheung Leung, Dr. Kwok Wai Cheung, Prof. Yiu Ming Cheung, Dr. Yu Zhang, and Dr. Fion Lee in our department, for their help, advice, and encouragement on my research during the past years. I also wish to thank Prof. Eugene Santos, Jr. at Dartmouth College (USA), Prof. Toru Ishida at Kyoto University (Japan), Prof. Michael Carter at University of Toronto (Canada), Prof. Bo Yang at Jilin University (China) for the valuable suggestions and encouragement to me. I sincerely thank the external examiners, Prof. Joseph Tan and Prof. Qing Li, for valuable comments and suggestions on the previous version of the thesis.

I would also like to acknowledge the past and present members in our AOC research group, they are, Dr. Benyun Shi, Mr. Shang Xia, Dr. Chao Gao, Dr. Zhiwen Yu, Mr. Xiaofei Yang, Dr. Lei Fan, Ms. Yuan Bai, Ms. Hongjun Qiu, Dr. Shuaiqiang Wang, and Mr. Lailei Huang. I greatly appreciate their help and kindness to me.

I want to thank our departmental staff, Mrs. Letty Kwok, Ms. Suan Choi, and Ms. Kristina Tsang. They helped me deal with lots of study related matters. I also

want to give my thanks to the technicians in our department, Ms. Leah Poon, Mr. S. Y. Leung, and Mr. Johnson Chow for their technical support.

I acknowledge the University Grants Committee (UGC) and the Research Grants Council (RGC) of Hong Kong as well as the Department of Computer Science at HKBU for the financial support provided to me throughout my study.

My sincerely thank my lovely and kindly roommates, Ms. Jue Wang, Ms. Xuanzi Cui, Ms. Huiming Li, Dr. Xiuhua Ni, for their encouragement and kindness to me.

Last, but not the least, I would like to give my heartfelt thanks to my husband, Liang Luo, and my parents for their endless love as well as spiritual support to me in my life.

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

Table of Contents

Abstract	ii
Acknowledgements	vi
Abbreviations	viii
Table of Contents	ix
List of Tables	xiv
List of Figures	xv
Chapter 1 Introduction	1
1.1 Background	2
1.2 Motivations and Objectives	8
1.2.1 Discovering the Direct, Indirect, and Moderating Effects of Observed and Latent Factors	8
1.2.2 Estimating the Changes in Wait Times with Demographic Shifts	9
1.2.3 Designing and Evaluating Service Management Strategies . . .	11
1.2.4 Characterizing Tempo-Spatial Patterns in Wait Times	13
1.3 Contributions and Significance	16
1.4 Structure of the Thesis	21
Chapter 2 Literature Review	23
2.1 Healthcare Service Systems	23

2.1.1	Basic Notions and Concepts	24
2.1.2	Complexity and Self-Organization	26
2.2	Empirical Identification of Relationships between Variables	28
2.2.1	Types of Relationships	28
2.2.2	Multivariate Analysis	30
2.3	Characterization of System Behavior	34
2.3.1	Stochastic Modeling and Simulation	35
2.3.2	System Dynamics	37
2.3.3	Individual-Based Modeling	39
2.4	Summary	42

Chapter 3 Discovering the Effects of Demand Factors: On Service

Utilization of a Single Unit 43

3.1	Introduction	44
3.2	The Effects of Geodemographic Profiles	46
3.2.1	Hypotheses	46
3.2.2	The Conceptual Model	50
3.3	SEM Tests and Results	50
3.3.1	Geodemographic and Service Administrative Data in Ontario .	50
3.3.2	Two-Step SEM Tests	55
3.3.3	Test Results	56
3.4	Discussion	59
3.5	Summary	63

Chapter 4 Discovering the Effects of Supply Factors: On Wait Times

across Units 64

4.1	Introduction	65
4.2	The Effect of a Unit's Characteristics on the Wait Times in a Subsequent Unit	70
4.2.1	Hypotheses	70

4.2.2	The Conceptual Model	73
4.3	SEM Tests and Results	74
4.3.1	Service Administrative Data in Ontario	74
4.3.2	SEM Tests	78
4.3.3	Test Results	79
4.4	Discussion	83
4.5	Summary	86
Chapter 5 Projecting the Changes of Service Performance		89
5.1	Introduction	90
5.2	Integrated Projection	93
5.2.1	SEM-Based Analysis	94
5.2.2	Projection	95
5.2.3	Queueing Model Simulation	96
5.3	Estimating the Performance of Cardiac Surgery Services	98
5.3.1	Demographic and Service Administrative Data in Ontario	98
5.3.2	Relationships between Demographic Factors and Service Characteristics	99
5.3.3	Service Performance Projection	101
5.3.4	The MSMQ-EC Queueing Model	102
5.3.5	Projection Results	103
5.4	Summary	107
Chapter 6 Designing and Evaluating an Adaptive Strategy for Service Management		108
6.1	Introduction	109
6.2	Designing an Adaptive OR Time Block Allocation Strategy	111
6.3	Modeling OR Services	113
6.4	Simulation-Based Experiments	115
6.4.1	Experimental Settings	115

6.4.2	Experimental Results	116
6.5	Discussion	117
6.6	Summary	121
Chapter 7 Characterizing the Tempo-Spatial Patterns in Patient Arrivals and Wait Times		123
7.1	Introduction	124
7.2	Empirical Tempo-Spatial Patterns in Cardiac Surgery Services	128
7.2.1	Aggregated Data	129
7.2.2	Statistical Regularities	130
7.2.3	Spatial Patterns	132
7.2.4	Temporal Patterns	136
7.3	AOC-CSS Modeling	139
7.3.1	Identifying Key Elements in Modeling	139
7.3.2	Modeling Environment	142
7.3.3	Modeling Entities	144
7.3.4	Designing Behavioral Rules	147
7.4	Simulation-Based Experiments	149
7.4.1	Experimental Settings	150
7.4.2	Statistical Regularities in Patient Arrivals and Wait Times . .	152
7.4.3	Patient-Attraction and Patient-Distribution Degrees of LHINs	154
7.4.4	Tempo-Spatial Patterns in Patient Arrivals and Wait Times .	155
7.5	Discussion	156
7.5.1	Explaining the Underlying Causes of Tempo-Spatial Patterns .	156
7.5.2	Sensitivity Analysis	163
7.6	Summary	167
Chapter 8 Conclusions and Future Work		168
8.1	Summary	168
8.2	Future Work	172

Bibliography

175

Curriculum Vitae

202