



MODELLING IN HEALTHCARE

COMPLEX SYSTEMS MODELLING GROUP



Applied
Mathematics

MODELLING IN HEALTHCARE



CSMG

COMPLEX SYSTEMS MODELLING GROUP

MODELLING IN HEALTHCARE



CSMG

COMPLEX SYSTEMS MODELLING GROUP

2010 *Mathematics Subject Classification*. Primary 00A06, 00A71, 97Mxx.

For additional information and updates on this book, visit
www.ams.org/bookpages/mbk-74

Library of Congress Cataloging-in-Publication Data

Modelling in healthcare / Complex Systems Modelling Group (CSMG).

p. cm.

Includes bibliographical references and index.

ISBN 978-0-8218-4969-9 (alk. paper)

1. Medical care—Research—Mathematical models. 2. Modeling. I. Simon Fraser University. Complex Systems Modelling Group. II. American Mathematical Society.

[DNLM: 1. Delivery of Health Care—organization & administration. 2. Models, Theoretical. 3. Artificial Intelligence. 4. Sociometric Techniques. W 26.5 M689 2010]

R853.M3M63 2010
610.72—dc22

2010009618

Copying and reprinting. Individual readers of this publication, and nonprofit libraries acting for them, are permitted to make fair use of the material, such as to copy a chapter for use in teaching or research. Permission is granted to quote brief passages from this publication in reviews, provided the customary acknowledgment of the source is given.

Republication, systematic copying, or multiple reproduction of any material in this publication is permitted only under license from the American Mathematical Society. Requests for such permission should be addressed to the Acquisitions Department, American Mathematical Society, 201 Charles Street, Providence, Rhode Island 02904-2294 USA. Requests can also be made by e-mail to reprint-permission@ams.org.

© 2010 by the American Mathematical Society. All rights reserved.
The American Mathematical Society retains all rights
except those granted to the United States Government.
Printed in the United States of America.

⊗ The paper used in this book is acid-free and falls within the guidelines
established to ensure permanence and durability.
Visit the AMS home page at <http://www.ams.org/>

10 9 8 7 6 5 4 3 2 1 15 14 13 12 11 10

Contents

Preface	ix
Acknowledgments	xi
Complex Systems Modelling Group	xiii
List of Figures	xv
List of Tables	xvii
Part 1. Modelling in Healthcare	
Chapter 1. The Whys, Whats, and Whens of Modelling in Healthcare	3
1. Why Model in Healthcare?	3
2. What Is a Model?	4
3. When to Use Modelling in Healthcare	5
4. Related Reading	6
Chapter 2. How to Use This Book	7
1. The Language of Modellers	8
Chapter 3. The Modelling Process	11
1. Selecting a Modelling Approach	12
2. Forming a Conceptual Model	16
3. Data Collection, Processing, and Analysis	16
4. Implementing and Validating the Model	17
5. Applying the Model	18
6. Revising the Model	19
7. Example	19
8. Related Reading	20
Part 2. Data Collection and Statistical Models	
Chapter 4. Issues of Data	25
Data Collection and Data Errors	25
1. Overview	25
2. Types of Data	25
3. Data Quality and Data Biases	29
4. Related Reading	32

Chapter 5. The Basics	33
Descriptive Statistics and Distributions	33
1. Model Overview	33
2. Common Uses	35
3. Mathematical Details	35
4. Examples	42
5. Related Reading	48
Chapter 6. Predictions and Responses	49
Regression Analysis	49
1. Model Overview	49
2. Common Uses	51
3. Mathematical Details	51
4. Examples	57
5. Related Reading	63
Chapter 7. Evaluating Detrimental Behaviour	65
Epidemiological Risk Modelling	65
1. Model Overview	65
2. Common Uses	67
3. Model Details	68
4. Examples	73
5. Related Reading	79
Chapter 8. Adjusting Risky Behaviour	81
Psychosocial Risk Modelling	81
1. Model Overview	81
2. Common Uses	83
3. Model Details	83
4. Examples	85
5. Related Reading	89
Part 3. Model Design and Interpretation	
Chapter 9. Issues in Mathematical Modelling	93
Model Selection, Development, and Implementation	93
1. Overview	93
2. Selecting a Modelling Technique	94
3. Developing the Model	95
4. Implementation of Models	96
5. Related Reading	100
Chapter 10. Explaining Irrational Behaviour	101
Psychosocial Modelling	101
1. Model Overview	101
2. Common Uses	102
3. Model Details	103

4. Examples	107
5. Related Reading	111
Chapter 11. Modelling Optimal Behaviour	113
Game Theory and Human Capital Models	113
1. Model Overview	113
2. Common Uses	115
3. Mathematical Details	115
4. Examples	120
5. Related Reading	123
Chapter 12. Modelling Social Interaction	125
Network Models and Graph Theory	125
1. Model Overview	125
2. Common Uses	126
3. Mathematical Details	127
4. Examples	129
5. Related Reading	134
Chapter 13. The Future Starts Now	135
Markov Models	135
1. Model Overview	135
2. Common Uses	137
3. Mathematical Details	137
4. Examples	142
5. Related Reading	149
Chapter 14. Viewing the System as a Whole	151
System Dynamics and Systems Thinking	151
1. Model Overview	151
2. Common Uses	153
3. Mathematical Details	154
4. Examples	156
5. Related Reading	162
Chapter 15. Dealing with Lines and Capacity	165
Queueing and Traffic Models	165
1. Model Overview	165
2. Common Uses	167
3. Mathematical Details	167
4. Examples	172
5. Related Reading	178
Chapter 16. Finding the “Best” Intervention	181
Optimization	181
1. Model Overview	181
2. Common Uses	182

3. Mathematical Details	183
4. Examples	191
5. Related Reading	195
Appendix. Computer Programming Packages Useful in Modelling	197
1. Statistical Software	197
2. Mathematical Software	197
3. Simulation and Modelling Codes	198
Bibliography	205
Index	215

Preface

As healthcare systems worldwide face the challenge of delivering quality services while maintaining control over escalating costs, there is growing support for the view that conventional approaches to the organization of healthcare systems are failing. The questions arising are extremely complex, and in most cases it is not acceptable to rely on simple intuition to answer a given question. In order to develop solid, defensible, evidence-based answers to the complex questions arising in modern healthcare, modelling is being increasingly applied. Yet, to many healthcare policymakers, the development, tuning, testing, validation, and eventual application of a model are considered a foreign art.

A model is a simplified representation of a real-world situation used to help answer a specific question. The main role of a model is to help steer decisions in the right direction. In most cases a model cannot give the “right” answer to a problem, but it can be a useful tool in characterizing the problem and finding ways to resolve it. In this book we provide a look into the world of modelling, with particular focus on modelling in healthcare. We provide this as it is our belief that decision makers and modellers must share a certain level of knowledge to maintain a healthy relationship. Modellers working on healthcare problems cannot be blind to the less mathematical issues of healthcare, and decision makers engaging modellers should not view models as mystical crystal balls from which answers emerge. As the Complex Systems Modelling Group, we have worked extensively with healthcare policymakers and have developed expertise in developing and analyzing healthcare models and in explaining models and modelling to those unfamiliar with the subject. With this book we hope to use this expertise to help strengthen the bonds between the worlds of modelling and healthcare.

This book is by no means a complete text on the subject of modelling in healthcare. In fact each chapter in this book (with the exception of the introductory chapters) could easily be extended into a complete textbook. We hope readers will view this as a handbook of modelling in healthcare and use it to provide themselves with a broad overview of how modelling works and what it is capable of.

As a handbook of modelling techniques, each chapter of this book has been written in a self-contained manner. Any given chapter can be read without having read previous chapters (although we strongly recommend reading the introductory chapters before tackling other chapters). Any text cross-reference to a section (or subsection) refers to that section (or subsection) in the current chapter unless otherwise specified. With the exception of the introductory chapters, each chapter focuses on a particular style of modelling that is applicable to healthcare. To keep the book as self-contained as possible, most chapters contain enough background that they are accessible to anyone with a solid high school level of mathematics. To ease reading, most chapters are written using the same basic template consisting

of *Model Overview*, *Common Uses*, *Model or Mathematical Details*, *Examples*, and *Related Reading*. Readers can quickly scan the model overview and common uses sections to determine if a model is applicable to the problem they are interested in and can study the mathematical details and examples sections if more detail is desired. The related reading section points readers to further literature of interest.

It is our hope that this book will provide a stepping stone for people interested in the world of modelling in healthcare, while remaining an excellent reference guide for those more familiar with the subject. As such, this book should be of use to anyone, academic or professional, who is interested in broadening his or her knowledge regarding modelling in healthcare.

Acknowledgments

The creation of this book began when the British Columbia Ministry of Health Services commissioned the Complex Systems Modelling Group (CSMG) at Simon Fraser University to produce a report on the many different mathematical options for modelling healthcare demand. For some of us this was a first step into the world of mathematical modelling specifically for healthcare – a step that has become a defining moment in many of our lives. We would like to thank the British Columbia Ministry of Health Services for funding the original report and for their continued support during the completion of this book.

Like any large team project, the production of the final manuscript for this book was a long and complicated process. Without the assistance of the many contributing authors (listed on page xiii) the final product would have been less than it is. Nonetheless, as with any large team project, there are certain individuals whose roles were more pivotal in the completion of this work. In this respect we would like to acknowledge authors Hare, Rutherford, and Vásárhelyi, as principal authors responsible for the original report and this book.

Finally, we would like to express our gratitude to the Centre for Interdisciplinary Research in the Mathematical and Computational Sciences (IRMACS, <http://www.irmacs.sfu.ca>) at Simon Fraser University. We are deeply indebted to IRMACS for its continual support during the production of this work. Many barriers could never have been crossed without the aide of the strong team of IRMACS administrative and technical support staff.

*Peter Borwein, Executive Director, CSMG
October 2009*

Complex Systems Modelling Group

Authors

Azadeh Alimadad, M.Sc.
Biostatistics

Alex Borwein
Health Sciences

Peter Borwein, Ph.D.
Mathematics

Vahid Dabbaghian, Ph.D.
Mathematics

Chiaka Drakes, M.Sc.
Mathematics, Education

Ron Ferguson, Ph.D.
Mathematics

Amir H. Ghaseminejad, M.Sc.
Engineering, Social Modelling

Yuri Gusev, Ph.D.
Theoretical Physics

Warren Hare*, Ph.D.
Mathematics, Operations Research

Jenny Li, M.Sc.
Mathematics

Snezana Mitrovic-Minic, Ph.D.
Operations Research

Alexander Rutherford*, Ph.D.
Queueing Theory, Physics

Alexa van der Waall, Ph.D.
Mathematics

Krisztina Vásárhelyi*, Ph.D.
Epidemiology, Genetics

Les Vertesi, M.D.
Epidemiology, Health Policy

* Principal Authors

List of Figures

Chapter 3		
Figure 3.1.	The modelling process	12
Chapter 5		
Figure 5.1.	Various probability distributions	40
Figure 5.2.	An example of poor descriptive statistics	42
Figure 5.3.	Age versus proximity to death in healthcare expenditures	44
Chapter 6		
Figure 6.1.	Linear regression example	52
Figure 6.2.	Examples of logistic curves	56
Figure 6.3.	Toes stubbed by number of stairs	58
Figure 6.4.	Linear fit to toes stubbed by number of stairs	59
Figure 6.5.	Logistic fit to toes stubbed by number of stairs	60
Figure 6.6.	Post-surgery knee extension recovery curves	62
Chapter 7		
Figure 7.1.	Simulation flow in the PREVENT Model	78
Chapter 9		
Figure 9.1.	Simple feedback loop	95
Chapter 10		
Figure 10.1.	Feedback loops in a simple influence diagram	106
Figure 10.2.	Feedback loops for the Behavioural Model of Healthcare	107
Figure 10.3.	Examining the Health Belief Model with respect to mammography visits	110
Chapter 12		
Figure 12.1.	Types of networks	128
Figure 12.2.	Cellular automata model of HIV spread	130
Figure 12.3.	Network of healthcare facilities	131
Figure 12.4.	Birthrates of Germany and Portugal	132
Figure 12.5.	Ising model analysis of birthrate drop-off	133

Chapter 13

Figure 13.1.	The SIR model of disease spread	136
Figure 13.2.	Testing the Markov assumption	140
Figure 13.3.	A three-state Markov model of BMI status	144
Figure 13.4.	Mover-stayer model of epidemic drug use	147

Chapter 14

Figure 14.1.	Systems thinking model relating new medicines to medicinal errors	152
Figure 14.2.	System dynamics model relating new medicines to medicinal errors	155
Figure 14.3.	Factors impacting hospital operating procedures	157
Figure 14.4.	Systems thinking model examining three factors in human weight cycling	159
Figure 14.5.	Human weight cycling plots suggested by Goldbeter's model	160

Chapter 15

Figure 15.1.	A multiple service channel queue	168
Figure 15.2.	A multiple service stage queue	169
Figure 15.3.	Queueing models reaching various equilibrium states	171
Figure 15.4.	Dishwashing queue	173
Figure 15.5.	Hospital patient flow queue	175

Chapter 16

Figure 16.1.	The difficulty with non-convex optimization	187
--------------	---	-----

List of Tables

Chapter 3		
Table 3.1.	Models in this book	13
Chapter 4		
Table 4.1.	Common data collection methods	26
Chapter 5		
Table 5.1.	Potential outcomes of summing two rolled dice	37
Table 5.2.	Probability table for the sum of two rolled dice	38
Table 5.3.	Hypothetical data regarding various headache medications	42
Table 5.4.	Survey of accommodation environments in BC	46
Table 5.5.	Non-publicly funded accommodation environments in BC	47
Chapter 6		
Table 6.1.	Artificial data of car-related costs and mileage by month	52
Table 6.2.	Artificial data of toes stubbed in the office	58
Chapter 7		
Table 7.1.	Artificial data relating chocolate and chickenpox	73
Table 7.2.	Demonstration of <i>Publication Bias In Situ</i>	76
Table 7.3.	Second demonstration of <i>Publication Bias In Situ</i>	77
Chapter 8		
Table 8.1.	Potential effect of a slow reduction in sodium intake	89
Chapter 10		
Table 10.1.	Elements in the Health Belief Model	105
Chapter 11		
Table 11.1.	Payoff table for the <i>Prisoner's Dilemma</i>	116
Table 11.2.	A payoff table solved by dominance	118
Chapter 13		
Table 13.1.	Data for a hypothetical doctor-patient loyalty model	142
Table 13.2.	Coupled difference equations represented by Figure 13.4	148

Bibliography

- [1] J.J. Abramson and Z.H. Abramson. *Survey Methods in Community Medicine: Epidemiological Research, Programme Evaluation, Clinical Trials*. Churchill Livingstone, London, UK, 1999.
- [2] E. Akcali. A network flow model for health care resource planning. In *INFORMS Optimization Society Conference: Optimization and Health Care*, San Antonio, Texas, February 3–5, 2006.
- [3] G. Albrecht, S. Freeman, and N. Higginbotham. Complexity and human health: The case for a transdisciplinary paradigm. *Culture Medicine and Psychiatry*, 22(1):55–92, 1998.
- [4] Azadeh Alimadad, Peter Borwein, Vahid Dabbaghian-Abdoly, Ron Ferguson, Ellen Fowler, Yuri Gusev, Michael Hayes, Warren Hare, Michel Joffre, Snezana Mitrovic-Minic, A. R. Rutherford, Krisztina Vasarhelyi, and Les Vertesi. How many more cases are needed? A report on hip and knee surgery waits in British Columbia. Technical report, CSMG Technical Report, IRMACS, Simon Fraser University, 2006. Prepared for the British Columbia Ministry of Health Services.
- [5] Ronald M. Andersen. Behavioral model of families’ use of health services, 1968. Research Series No. 25. Chicago, IL: Center for Health Administration Studies, University of Chicago.
- [6] Ronald M. Andersen. Revisiting the behavioral model and access to medical care: Does it matter? *Journal of Health and Social Behavior*, 36(1):1–10, 1995.
- [7] T. Andersson and P. Várbrand. Decision support tools for ambulance dispatch and relocation. *Journal of the Operational Research Society*, pages 1–7, 2006.
- [8] Margarete Arndt and Barbara Bigelow. Commentary: The potential of chaos theory and complexity theory for health services management. *Health Care Management Review*, 25(1):35–38, 2000.
- [9] Kenneth J. Arrow. Uncertainty and the welfare economics of medical care. *The American Economic Review*, 53(5):941–973, 1963.
- [10] C. Audet and J. E. Dennis, Jr. Mesh adaptive direct search algorithms for constrained optimization. *SIAM J. Optim.*, 17(1):188–217 (electronic), 2006.
- [11] Thomas Bäck. *Evolutionary algorithms in theory and practice*. The Clarendon Press, Oxford University Press, New York, 1996. Evolution strategies, evolutionary programming, genetic algorithms.
- [12] Rose D. Baker. Sensitivity analysis for healthcare models fitted to data by statistical methods. *Health Care Management Science*, 5(4):275–281, 2002.
- [13] Osman Balci. Verification, validation and accreditation of simulation models. In S. Andradttir, K. J. Healy, D. H. Withers, and B. L. Nelson, editors, *Proceedings of the 1997 Winter Simulation Conference*, pages 135–141, 1997.
- [14] Osman Balci. Quality assessment, verification, and validation of modeling and simulation applications. In R. G. Ingalls, M. D. Rossetti, J. S. Smith, and B. A. Peters, editors, *Proceedings of the 2004 Winter Simulation Conference*, pages 122–129, 2004.
- [15] A. Bandura. Health promotion by social cognitive means. *Health Education and Behavior*, 31:143–164, 2004.
- [16] Yaneer Bar-Yam. Improving the effectiveness of health care and public health: A multiscale complex systems analysis. *American Journal of Public Health*, 96:459–466, 2006.
- [17] Forest Baskett, K. Mani Chanday, Richard R. Muntz, and Fernando G. Palacios. Open, closed, and mixed networks of queues with different classes of customers. *J. Assoc. Comput. Mach.*, 22:248–260, 1975.
- [18] Gary S. Becker. Investment in human capital: A theoretical analysis. *The Journal of Political Economy*, 70:9–49, 1962.

- [19] Gary S. Becker. *The Economic Approach to Human Behaviour*. University of Chicago Press, Chicago, 1976.
- [20] Gary S. Becker. The economic way of looking at life, 1992. Nobel Lecture, December 9, 1992.
- [21] Gary S. Becker. *Human Capital: A Theoretical and Empirical Analysis with Special Reference to Education*. University of Chicago Press, Chicago, 1993.
- [22] Gary S. Becker and Kevin M. Murphy. A theory of rational addiction. *The Journal of Political Economy*, 96:675–700, 1988.
- [23] Gary Stanley Becker. Human capital and personal distribution of income: an analytical approach. In *Woytinsky lecture no. 1*. Ann Arbor: Institute of Public Administration, 1967.
- [24] C. M. Bell, M. Crystal, A. S. Detsky, and D. A. Redelmeier. Shopping around for hospital services: a comparison of the United States and Canada. *JAMA: The Journal of the American Medical Association*, 279(13):1015–1017, 1998.
- [25] S. Bergheim. *Live long and prosper! Health and longevity as growth drivers*. Deutsche Bank Research, Frankfurt, Germany, March 2006.
- [26] P. P. Biemer and L. E. Lyberg. *Introduction to Survey Quality*. John Wiley and Sons, Inc., New Jersey, 2003.
- [27] L. Billard. Markov models and social analysis. *International Encyclopedia of the Social and Behavioural Sciences*, pages 9242–9250, 2004.
- [28] John T. Blake and Michael W. Carter. An analysis of emergency room wait time issues via computer simulation. *INFOR*, 34(4):263–273, 1996.
- [29] Kristian Bolin, Lena Jacobson, and Björn Lindgren. The family as the health producer — when spouses are Nash-bargainers. *Journal of Health Economics*, 20:349–362, 2001.
- [30] Kristian Bolin, Lena Jacobson, and Björn Lindgren. The family as the health producer — when spouses act strategically. *Journal of Health Economics*, 21:475–495, 2002.
- [31] J. Frédéric Bonnans, J. Charles Gilbert, Claude Lemaréchal, and Claudia A. Sagastizábal. *Numerical optimization*. Universitext. Springer-Verlag, Berlin, second edition, 2006. Theoretical and practical aspects.
- [32] K. Boulding. *Economic Analysis*. Harper and Row, New York, 1966.
- [33] Stephen Boyd and Lieven Vandenberghe. *Convex optimization*. Cambridge University Press, Cambridge, 2004. <http://www.stanford.edu/~boyd/cvxbook/>.
- [34] S. C. Brailsford, V. A. Lattimer, P. Tarnaras, and J. C. Turnbull. Emergency and on-demand health care: modelling a large complex system. *Journal of the Operational Research Society*, 55(1):34–42, 2004.
- [35] H. Bronnum-Hansen. How good is the Prevent model for estimating the health benefits of prevention? *J. Epidemiol. Community Health*, 53:300–305, 1999.
- [36] L. Brotcorne, G. Laporte, and F. Semet. Ambulance location and relocation models. *European Journal of Operational Research*, 147(3):451–463, 2003.
- [37] B. Burström and P. Fredlund. Self rated health: Is it as good a predictor of subsequent mortality in lower as well as in higher social classes? *J. Epidemiol. Community Health*, 55:836–840, 2001.
- [38] Barbara M. Byrne. *Structural Equation Modeling with AMOS*. CRC Press, second edition, 2009.
- [39] A. C. Cameron and P. K. Trivedi. *Regression analysis of count data*. Cambridge University Press, Cambridge, UK, 1998.
- [40] A. C. Cameron, P. K. Trivedi, F. Milne, and J. Piggott. A microeconomic model of the demand for health care and health insurance in Australia. *The Review of Economic Studies*, 55:85–106, 1988.
- [41] John S. Carson. Introduction to modeling and simulation. In R. G. Ingalls, M. D. Rossetti, J. S. Smith, and B. A. Peters, editors, *Proceedings of the 2004 Winter Simulation Conference*, pages 9–16, 2004.
- [42] Robert Y. Cavana, Philip K. Davies, Rachel M. Robson, and Kenneth J. Wilson. Drivers of quality in health services: different worldviews of clinicians and policy managers revealed. *System Dynamics Review (Wiley)*, 15(3):331–340, 1999.
- [43] Harry Clarke and Svetlana Danilkina. Talking rationally about rational addiction. Preprint, Dept. of Economics, La Trobe University, 2006.

- [44] Jeffery K. Cochran and Aseem Bharti. A multi-stage stochastic methodology for whole hospital bed planning under peak loading. *International Journal of Industrial and Systems Engineering*, 1:8–36, 2006.
- [45] J. E. Cohen and B. Singer. Malaria in Nigeria: Constrained continuous-time Markov models for discrete-time longitudinal data on human mixed-species infections. In *Some Mathematical Questions in Biology*, pages 69–133. Providence: American Mathematical Society, 1979.
- [46] A. D. Colle and M. Grossman. Determinants of pediatric care utilization. *The Journal of Human Resources*, 13 Suppl:115–158, 1978.
- [47] T. Collings and C. Stoneman. The $M/M/\infty$ queue with varying arrival and departure rates. *Operations Res.*, 24(4):760–773, 1976.
- [48] A. R. Conn, K. Scheinberg, and Ph. L. Toint. Recent progress in unconstrained nonlinear optimization without derivatives. *Math. Programming*, 79(1-3, Ser. B):397–414, 1997. Lectures on mathematical programming (ismp97) (Lausanne, 1997).
- [49] R. Cook and J. Rasmussen. “Going Solid”: a model of system dynamics and consequences for patient safety. *Quality & Safety in Health Care*, 14(2):130–134, 2005.
- [50] Ben Cooper and Marc Lipsitch. The analysis of hospital infection data using hidden Markov models. *Biostatistics (Oxford, England)*, 5(2):223–237, 2004.
- [51] Kenneth Craik. *The Nature of Explanation*. Cambridge University Press, Cambridge, 1943.
- [52] Thomas F. Crossley and Steven Kennedy. The reliability of self-assessed health status. *Journal of Health Economics*, 21:643–658, 2002.
- [53] John G. Cullis and Philip R. Jones. National health service waiting lists: A discussion of competing explanations and a policy proposal. *Journal of Health Economics*, 4(2):119–135, 1985.
- [54] V. Dabbaghian, K. Vasarhelyi, N. Richardson, P. Borwein, and A. R. Rutherford. The impact of social interactions on the spread of HIV infection among injection drug users: A Cellular Automaton model. Technical report, CSMG Technical Report, IRMACS, Simon Fraser University, 2008.
- [55] B. Dangerfield and C. Roberts. Fitting a model of the spread of AIDS to data from five European countries. In *O.R. Work in HIV/AIDS*, pages 7–13, Birmingham, 1994.
- [56] B. Dangerfield and C. Roberts. Foreword to the special issue on health and health care dynamics. *System Dynamics Review (Wiley)*, 15(3):197–199, 1999.
- [57] B. Dangerfield and C. Roberts. Optimisation as a statistical estimation tool: an example in estimating the AIDS treatment-free incubation period distribution. *System Dynamics Review (Wiley)*, 15(3):273–291, 1999.
- [58] B. C. Dangerfield. System dynamics applications to European health care issues. *The Journal of the Operational Research Society*, 50(4):345–353, 1999.
- [59] M. S. Daskin. A maximum expected coverage location model: Formulation, properties and heuristic solution. *Transportation Science*, 17:48–70, 1983.
- [60] M. S. Daskin and L. K. Dean. Location of health care facilities. In M. L. Brandeau, F. Sainfort, and W. P. Pierskalla, editors, *Operations research and health care: A handbook of methods and applications*, International series in operations research and management science, pages 43–76. Kluwer, Boston, 2004.
- [61] Paul Davidsson. Agent based social simulation: A computer science view. *Journal of Artificial Societies and Social Simulation*, 5(1), 2002.
- [62] G. A. Diamond, A. Rozanski, and M. Steuer. Playing doctor: application of game theory to medical decision-making. *Journal of Chronic Diseases*, 39:669–677, 1986.
- [63] P. Diehr, D. Yanez, A. Ash, M. Hornbrook, and D. Y. Lin. Methods for analyzing health care utilization and costs. *Annual Review of Public Health*, 20:125–144, 1999.
- [64] Ana V. Diez-Roux. Multilevel analysis in public health research. *Annu. Rev. Public Health*, 21:171–192, 2000.
- [65] Eddy K. A. Van Doorslaer. *Health, Knowledge and the Demand for Medical Care: an econometric analysis*. Van Gorcum, Assen/Maastricht, 1987.
- [66] Marco Dorigo and Christian Blum. Ant colony optimization theory: a survey. *Theoret. Comput. Sci.*, 344(2-3):243–278, 2005.
- [67] Steven B. Dowd. Applied game theory for the hospital manager: Three case studies. *The Health Care Manager*, 23:156–161, 2004.
- [68] F. Y. Edgeworth. *Mathematical Psychics*. Kegan Paul, London, 1881.

- [69] Matthew J. Eichner. The demand for medical care: What people pay does matter. *American Economic Review*, 88(2):117–121, 1998.
- [70] J. E. Everett. A decision support simulation model for the management of an elective surgery waiting system. *Health Care Management Science*, 5(2):89–95, 2002.
- [71] Michael G. Farnworth. A game theoretic model of the relationship between prices and waiting times. *Journal of Health Economics*, 22:47–60, 2003.
- [72] Centre for Disease Control and Prevention. HIV/AIDS Surveillance Report, 2007. Technical report, Department of Health and Human Services, Centres for Disease Control and Prevention, Atlanta, USA, 2009.
- [73] Mario Forni and Marco Lippi. Aggregation of linear dynamic microeconomic models. *Journal of Mathematical Economics*, 31(1):131–158, 1999.
- [74] Jay W. Forrester. *Industrial dynamics*. Pegasus Communications, Waltham, MA, 1961.
- [75] Jay W. Forrester. System dynamics and the lessons of 35 years. In Kenyon B. de Greene, editor, *The Systemic Basis of Policy Making in the 1990s*. MIT Press, 1991.
- [76] Jay W. Forrester. System dynamics, systems thinking, and soft OR. *System Dynamics Review (Wiley)*, 10(2/3):245–256, 1994.
- [77] Jay W. Forrester. The beginning of system dynamics. *McKinsey Quarterly*, 4:4–16, 1995.
- [78] The Framingham heart study, 2002. <http://www.nhlbi.nih.gov/about/framingham>.
- [79] J. F. Fries, C. E. Koop, J. Sokolov, C. E. Beadle, and D. Wright. Beyond health promotion: reducing need and demand for medical care. *Health Affairs*, 17:70–84, 1998.
- [80] World Cancer Research Fun. Food, nutrition, physical activity and the prevention of cancer: A global perspective. Technical report, World Cancer Research Fund, 2007.
- [81] Mauro Gallegato and Alan Kirman, editors. *Beyond the representative agent*. Edward Elgar, Cheltenham, UK, 1999.
- [82] Mauro Gallegato, Alan P. Kirman, and Matteo Marsili, editors. *The Complex Dynamics of Economic Interaction: Essays in Economics and Econophysics*, Volume 531 of *Lecture Notes in Economics and Mathematical Systems*. Springer, Berlin, 2004.
- [83] M. Gendreau, G. Laporte, and F. Semet. A dynamic model and parallel tabu search heuristic for real-time ambulance relocation. *Parallel Computing*, 27:1641–1653, 2001.
- [84] Jon Gjerde, Sverre Grepperud, and Snorre Kverndokk. On adaptation and the demand for health. *Applied Economics*, 37:1283–1301, 2005.
- [85] F. Glover and M. Laguna. *Tabu Search*. Springer, New York, 1997.
- [86] J. B. Goldberg. Operations research models for the deployment of emergency services vehicles. *EMS Management Journal*, 1(1):20–39, 2004.
- [87] A. Goldbeter. A model for the dynamics of human weight cycling. *J. Biosci.*, 31:129–136, 2006.
- [88] B. González-Busto and R. García. Waiting lists in Spanish public hospitals: a system dynamics approach. *System Dynamics Review (Wiley)*, 15(3):201–224, 1999.
- [89] Leo A. Goodman. Statistical methods for the Mover-Stayer model. *Journal of the American Statistical Association*, 56:841–868, 1961.
- [90] Florin Gorunescu, Sally I. McClean, and Peter H. Millard. Using a queueing model to help plan bed allocation in a department of geriatric medicine. *Health Care Management Science*, 5(4):307–312, 2002.
- [91] Linda V. Green and Sergei Savin. Reducing delays for medical appointments: a queueing approach. *Oper. Res.*, 56(6):1526–1538, 2008.
- [92] Michael Grossman. On the concept of health capital and the demand for health. *The Journal of Political Economy*, 80:223–255, 1972.
- [93] Martin Grötschel, Sven O. Krumke, and Jörg Rambau, editors. *Online optimization of large scale systems*. Springer-Verlag, Berlin, 2001.
- [94] Louise Gunning-Schepers. *The Health Benefits of Prevention*. Elsevier, Amsterdam, 1989.
- [95] David C. Hadorn. Setting priorities on waiting lists: point-count systems as linear models. *Journal of Health Services Research and Policy*, 8:48–54, 2003.
- [96] Jahn Karl Hakes and W. Kip Viscusi. Dead reckoning: Demographic determinants of the accuracy of mortality risk perceptions. *Risk Analysis*, 24:651–664, 2004.
- [97] Randolph W. Hall. Patient flow. *OR/MS Today*, 33(3), 2006.
- [98] Marianne Hanning. Maximum waiting-time guarantee – an attempt to reduce waiting lists in Sweden. *Health Policy*, 36(1):17–35, 1996.

- [99] Marianne Hanning and Ulrika Winblad Spangberg. Maximum waiting time – a threat to clinical freedom?: Implementation of a policy to reduce waiting times. *Health Policy*, 52(1):15–32, 2000.
- [100] L. Hansen. Large sample properties of generalized method of moments estimators. *Econometrica*, 50:1029–1054, 1982.
- [101] W. Hare and H. Dodd. Non-publicly funded accommodation environments in British Columbia: survey and analysis. Technical report, CSMG Technical Report, IRMACS, Simon Fraser University, 2008. Prepared for the British Columbia Ministry of Health Services.
- [102] W. L. Hare and G. Tanoh. Recovery rates for knee and hip surgery patients. Technical report, CSMG Technical Report, IRMACS, Simon Fraser University, 2007. Prepared for the Fraser Health Authority.
- [103] Robert Haveman, Barbara Wolfe, Brent Kreider, and Mark Stone. Market work, wages, and men’s health. *J. Health Econ.*, 13:163–182, 1994.
- [104] F.J. He and G.A. MacGregor. A comprehensive review on salt and health and current experience of worldwide salt reduction programmes. *Journal of Human Hypertension*, 23:363–384, 2009.
- [105] J. Heckman and B. Singer. A method for minimizing the impact of distributional assumptions in econometric models for duration data. *Econometrica*, 52:271–320, 1984.
- [106] S. G. Henderson and A. J. Mason. Ambulance service planning: Simulation and data visualisation. In M. L. Brandeau, F. Sainfort, and W. P. Pierskalla, editors, *Operations research and health care: A handbook of methods and applications*, International series in operations research and management science, pages 78–102. Kluwer, Boston, 2004.
- [107] Gary Hirsch and C. Sherry Immediato. Microworlds and generic structures as resources for integrating care and improving health. *System Dynamics Review (Wiley)*, 15(3):315–330, 1999.
- [108] Gary B. Hirsch. System dynamics modeling in health care. *SIGSIM Simul. Dig.*, 10(4):38–42, 1979.
- [109] Marna Hoard, Jack Homer, William Manley, Paul Furbee, Arshadul Haque, and James Helmkamp. Systems modeling in support of evidence-based disaster planning for rural areas. *International Journal of Hygiene and Environmental Health*, 208(1-2):117–125, 2005.
- [110] Michael Hoel and Erik Magnus Saether. Public health care with waiting time: the role of supplementary private health care. *Journal of Health Economics*, 22(4):599–616, 2003.
- [111] Jack Homer and Bobby Milstein. Optimal decision making in a dynamic model of community health. In *Proceedings of the 37th Annual Hawaii International Conference on System Sciences (HICSS’04)*, 2004.
- [112] Jack B. Homer and Gary B. Hirsch. System dynamics modeling for public health: Background and opportunities. *American Journal of Public Health*, 96:452–458, 2006.
- [113] Amanda A. Honeycutt, James P. Boyle, Kristine R. Broglio, Theodore J. Thompson, Thomas J. Hoerger, Linda S. Geiss, and K. M. Venkat Narayan. A dynamic Markov model for forecasting diabetes prevalence in the United States through 2050. *Health Care Management Science*, 6:155–164, 2003.
- [114] L. Hood, J. R. Heath, M. E. Phelps, and B. Lin. Systems biology and new technologies enable predictive and preventive medicine. *Science*, 306:640–643, 2004.
- [115] David W. Hosmer, Scott Taber, and Stanley Lemeshow. The importance of assessing the fit of logistic regression models: A case study. *American Journal of Public Health*, 81(12):1630, 1991.
- [116] Darrel Huff. *How to Lie with Statistics*. W. W. Norton & Company, New York, 1954.
- [117] J. S. Ivy and L. Maillart. Mathematical modeling of dynamic breast cancer screening policies. In *INFORMS Optimization Society Conference: Optimization and Health Care*, San Antonio, Texas, February 3–5, 2006.
- [118] Nancy K. Janz and Marshall H. Becker. The health belief model: A decade later. *Health Education Quarterly*, 11:1–47, 1984.
- [119] M.R. Joffres and A. Alimadad. Estimates of reductions in events from ischemic heart diseases, cerebrovascular diseases and heart failure in Canada following a 5 or 10% yearly reduction in sodium intake at the population level, and potential savings in hospital costs. Technical report, Faculty of Health Sciences, Simon Fraser University, 2009. Report for Public Health Agency of Canada – Sodium subgroup research committee.

- [120] M.R. Joffres, N.R. Campbell, B. Manns, and K. Tu. Estimate of the benefits of a population-based reduction in dietary sodium additives on hypertension and its related health care costs in Canada. *Canad. J. Cardiol.*, 6:437–443, 2007.
- [121] Andrew Jones. *Applied Econometrics for Health Economists*. Radcliffe Publishing Ltd, United Kingdom, 2007.
- [122] Andrew M. Jones. Health econometrics. In K. J Culyer and J. P. Newhouse, editors, *North-Holland Handbook of Health Economics*. North Holland, 2000.
- [123] Jay Ashvin Joseph. The applicability, usefulness, and limitations of the PREVENT model, as demonstrated by modeling the effects of alcohol consumption interventions on coronary heart disease mortality. Master’s thesis, Department of Community Health, University of Toronto, 1997.
- [124] Donald S. Kenkel. Health behavior, health knowledge, and schooling. *Journal of Political Economy*, 99(2):287–305, 1991.
- [125] D. M. Kennedy, S. E. Hanna, P. W. Stratford, J. Wessel, and J. D. Gollish. Preoperative function and gender predict pattern of functional recovery after hip and knee arthroplasty. *The Journal of Arthroplasty*, 21(4):559–566, 2006.
- [126] D. M. Kennedy, P. W. Stratford, S. E. Hanna, J. Wessel, and J. D. Gollish. Modeling early recovery of physical function following hip and knee arthroplasty. *BMC Musculoskeletal Disorders*, 7:100, 2006.
- [127] S. Kirkpatrick, C. D. Gelatt Jr., and M. P. Vecchi. Optimization by Simulated Annealing. *Science*, 220(4598):671–680, 1983.
- [128] Alan Kirman. Whom or what does the representative individual represent? *The Journal of Economic Perspectives*, 6:117–136, 1992.
- [129] Alan Kirman and Jean Benoit Zimmermann, editors. *Economics with Heterogeneous Interacting Agents*, Volume 503 of *Lecture Notes in Economics and Mathematical Systems*. Springer, Berlin, 2001.
- [130] Marie Fanelli Kuczmarski, Robert J. Kuczmarski, and Matthew Najjar. Effects of age on validity of self-reported height, weight, and body mass index: Findings from the third national health and nutrition examination survey, 1988-1994. *Journal of the American Dietetic Association*, 101(1):28–34, 2001.
- [131] Snorre Kverndokk. Why do people demand health? Technical report, Ragnar Frisch Centre for Economic Research, University of Oslo, 2000.
- [132] Kajal Lahiri and Guibo Xing. An econometric analysis of veterans’ health care utilization using two-part models. *Empirical Economics*, 29(2):431–449, 2004.
- [133] D. C. Lane, C. Monefeldt, and J. V. Rosenhead. Looking in the wrong place for healthcare improvements: A system dynamics study of an accident and emergency department. *Journal of the Operational Research Society*, 51(5):518–531, 2000.
- [134] David Lane, Camilla Monefeldt, and Jonathan Rosenhead. Emergency – but no accident — a system dynamics study of an accident and emergency department. *OR Insight*, 1998.
- [135] Jean K. Langlie. Social networks, health beliefs, and preventive health behavior. *Journal of Health and Social Behavior*, 18(3):244–260, 1977.
- [136] V. Lattimer, S. Brailsford, J. Turnbull, P. Tarnaras, H. Smith, S. George, K. Gerard, and S. Maslin-Prothero. Reviewing emergency care systems I: insights from system dynamics modelling. *Emerg. Med. J.*, 21(6):685–691, 2004.
- [137] R. M. Lewis and V. Torczon. A globally convergent augmented Lagrangian pattern search algorithm for optimization with general constraints and simple bounds. *SIAM J. Optim.*, 12(4):1075–1089, 2002.
- [138] Stephen Lewis and Claudia Sanmartin. Managing waiting lists to achieve distributive justice. A working paper prepared for the Western Canada Wait List Project.
- [139] Steven Lewis, Morris L. Barer, Claudia Sanmartin, Sam Sheps, Samuel E.D. Shortt, and Paul W. McDonald. Ending waiting-list mismanagement: principles and practice. *Canadian Medical Association Journal*, 162(9):1297–1300, 2000.
- [140] W. G. Liddell and J. H. Powell. Agreeing access policy in a general medical practice: a case study using QPID. *System Dynamics Review (Wiley)*, 20(1):49–73, 2004.
- [141] Cotton M. Lindsay and Bernard Feigenbaum. Rationing by waiting lists. *American Economic Review*, 74(3):404–417, 1984.
- [142] Chih-Ming Liu, Kuo-Ming Wang, and Yuh-Yuan Guh. A Markov chain model for medical record analysis. *The Journal of the Operational Research Society*, 42(5):357–364, 1991.

- [143] Mary V. Look. *Policy Systems and Their Complexity Dynamics: Academic Medical Centers and Managed Care Markets*. PhD thesis, Virginia Polytechnic Institute and State University, Virginia, 2003.
- [144] A. Mark, D. Pencheon, and R. Elliott. Demanding healthcare. *Int. J. Health Plann. and Mgmt.*, 15:237–253, 2000.
- [145] Brian J. Masterson, Thomas G. Mihara, George Miller, Stephen C. Randolph, M. Emma Forkner, and Andrew L. Crouter. Using models and data to support optimization of the military health system: A case study in an intensive care unit. *Health Care Management Science*, 7(3):217–224, 2004.
- [146] Roger McCain. *Game Theory: A Non-Technical Introduction to the Analysis of Strategy*. South-Western College Pub., 2003.
- [147] S. I. McClean, B. McAlea, and P. H. Millard. Using a Markov reward model to estimate spend-down costs for a geriatric department. *The Journal of the Operational Research Society*, 49(10):1021–1025, 1998.
- [148] K. M. McGrail, B. Green, M. L. Barer, R. G. Evans, C. Hertzman, and C. Normand. Age, costs of acute and long-term care and proximity to death: evidence for 1987-88 and 1994-95 in British Columbia. *Age and Ageing*, 29:249–253, 2000.
- [149] Beth E. Meyerowitz and Shelly Chaiken. The effect of message framing on breast self-examination attitudes, intentions, and behavior. *Journal of Personality and Social Psychology*, 52(3):500–510, 1987.
- [150] L. A. Meyers, M. E. J. Newman, M. Martin, and S. Schrag. Applying network theory to epidemics: Control measures for *mycoplasma pneumoniae* outbreaks. *Emerging Infectious Diseases*, 9:204–210, 2003.
- [151] Quentin Michard and Jean-Philippe Bouchaud. Theory of collective opinion shifts. *The European Physical Journal B — Condensed Matter and Complex Systems*, 47:151–159, 2005.
- [152] Olli S. Miettinen. Proportion of disease caused or prevented by a given exposure, trait or intervention. *American Journal of Epidemiology*, 99:325–332, 1974.
- [153] Bobby Milstein and Jack Homer. Background on systems dynamics simulation modeling, with a summary of major public health studies. Syndemics Prevention Network, May 2006.
- [154] Y. Mizuno, D. Wilkonson, S. Santibanez, C. Dawson Rose, A. Knowlton, K. Handley, M. N. Gourevitch, and INSPIRE Team. Correlates of health care utilization among HIV-seropositive injection drug users. *AIDS Care*, 18(5):417–425, 2006.
- [155] John Morecroft and Stewart Robinson. Comparing discrete-event simulation and system dynamics: modelling a fishery. In *Proceedings of the 2006 Operational Research Society Simulation Workshop, 28-29 March 2006*, pages 137–148. UK Operational Research Society, 2006.
- [156] Oskar Morgenstern and John von Neumann. *Theory of Games and Economic Behaviour*. Princeton University Press, 1944.
- [157] P. Mullen. Waiting lists in the post review NHS. *Health Service Management*, 7(2):131–145, 1994.
- [158] Mark Murray and Donald M. Berwick. Advanced Access: Reducing Waiting and Delays in Primary Care. *JAMA*, 289(8):1035–1040, 2003.
- [159] John F. Nash. *Non-cooperative Games*. PhD thesis, Princeton University, 1950.
- [160] Vicente Navarro, Rodger Parker, and Kerr L. White. A stochastic and deterministic model of medical care utilization. *Health Services Research*, 5(4):342–357, 1970.
- [161] J. A. Nelder and R. Mead. A simplex method for function minimization. *Comput. J.*, 7:308–313, 1965.
- [162] M. E. J. Newman. Spread of epidemic disease on networks. *Phys. Rev. E*, 66(1):16128–16139, 2002.
- [163] M. E. J. Newman. The structure and function of complex networks. *SIAM Review*, 45(2):167–256, 2003.
- [164] J. Nocedal and S. J. Wright. *Numerical optimization*. Springer Series in Operations Research and Financial Engineering. Springer, New York, second edition, 2006.
- [165] Tom Noseworthy. Top priority. *Canadian Healthcare Manager*, 11(6):43–44, 2004.
- [166] Ted O’Donoghue and Matthew Rabin. Risky behavior among youths: Some issues from behavioral economics. In Jon Gruber, editor, *Risky Behavior Among Youths*, pages 29–67. University of Chicago Press, Chicago, 2001.

- [167] Public Health Agency of Canada. HIV/AIDS epi updates, November 2007. Technical report, Surveillance and Risk Assessment Division, Centre for Infectious Disease Prevention and Control, Public Health Agency of Canada, 2007.
- [168] Rogelio Oliva. Model structure analysis through graph theory: partition heuristics and feedback structure decomposition. *System Dynamics Review (Wiley)*, 20(4):313–336, 2004.
- [169] Panel on Dietary Reference Intakes for Electrolytes and Standing Committee on the Scientific Evaluation of Dietary Reference Intakes Water. *Dietary Reference Intakes for Water, Potassium, Sodium, Chloride, and Sulfate*. National Academies Press, 2004.
- [170] World Health Organization. Fact sheet number 297: cancer. Technical report, WHO, 2006.
- [171] World Health Organization. Reducing salt intake in populations. Technical report, World Health Organization, 2007. Report of a WHO forum and technical meeting, 5-7 October 2006, Paris, France.
- [172] Mari Palta, Ronald J. Prineas, Reuben Berman, and Peter Hannan. Comparison of Self-Reported and Measured Height and Weight. *Am. J. Epidemiol.*, 115(2):223–230, 1982.
- [173] Bernice A. Pescosolido. Beyond rational choice: The social dynamics of how people seek help. *American Journal of Sociology*, 97:1096–1138, 1992.
- [174] Carl V. Phillips. Quantifying and reporting uncertainty from systematic errors. *Epidemiology*, 14(4):459–466, 2003.
- [175] Carl V. Phillips. Publication bias in situ. *BMC Medical Research Methodology*, 4, 2004.
- [176] Carl V. Phillips and Richard Zeckhauser. Communicating the health effects of consumer products: The case of moderate alcohol consumption and coronary heart disease. *Managerial and Decision Economics*, 17:459–470, 1996.
- [177] K. A. Phillips, K. R. Morrison, R. Andersen, and L. A. Aday. Understanding the context of healthcare utilization: assessing environmental and provider-related variables in the behavioral model of utilization. *Health Services Research*, 33(3, Pt. 1):571–596, 1998.
- [178] John P. Pierce, Michael C. Fiore, Thomas E. Novotny, Evridiki J. Hatzianreou, and Ronald M. Davis. Trends in cigarette smoking in the United States, projections to the year 2000. *Journal of the American Medical Association*, 261:61–65, 1989.
- [179] Paul E. Plsek and Trisha Greenhalgh. Complexity science: the challenge of complexity in health care. *British Medical Journal*, 323:625–628, 2001.
- [180] B. Pourbohloul, L. A. Meyers, D. M. Skowronski, M. Krajden, D. M. Patrick, and R. C. Brunham. Modeling control strategies of respiratory pathogens. *Emerging Infectious Diseases*, 11:1249–1256, 2005.
- [181] Nicolaas P. Pronk, Michael J. Goodman, Patrick J. O’Connor, and Brian C. Martinson. Relationship between modifiable health risks and short-term health care charges. *Journal of the American Medical Association*, 282:2235–2239, 1999.
- [182] H. N. Psaraftis. Dynamic vehicle routing problems. In B. L. Golden and A. A. Assad, editors, *Vehicle Routing: Methods and Studies*, Volume 16 of *Studies in Management Science and Systems*, pages 223–248. North-Holland, Amsterdam, 1988.
- [183] B. Ramadanović, A. van der Waall, A.R. Rutherford, L. Vertesi, Y. Wang, and I. Rongve. Performance Metrics and Service Discipline in a System-Scale Model of Surgical Wait List. In *Proceedings of the 35th International Conference on Operational Research Applied to Health Services (ORAHs)*, Leuven, Belgium, July 2009.
- [184] B. Rockhill, B. Newman, and C. Weinberg. Use and misuse of population attributable fractions. *American Journal of Public Health*, 88:15–19, 1998.
- [185] Thomas Rohleder, Diane Bischak, and Leland Baskin. Modeling patient service centers with simulation and system dynamics. *Health Care Management Science*, 10(1):1–12, 2007.
- [186] C. Roos, T. Terlaky, and J.-P. Vial. *Interior point methods for linear optimization*. Springer, New York, 2006. Second edition of *Theory and algorithms for linear optimization* [Wiley, Chichester, 1997; MR1450094].
- [187] Carla Rossi. Operational models for epidemics of problematic drug use: the Mover-Stayer approach to heterogeneity. *Socio-Economic Planning Sciences*, 38:73–90, 2004.
- [188] M. L. Rowland. Self-reported weight and height. *Am. J. Clin. Nutr.*, 52(6):1125–1133, 1990.
- [189] Geoff Royston, Ayesha Dost, Jeremy Townshend, and Howard Turner. Using system dynamics to help develop and implement policies and programmes in health care in England. *System Dynamics Review*, 15(3):293–313, 1999.

- [190] Claudia Sanmartin. Acceptable waiting times for medical services: A review of the evidence and proposed methods. A Working Paper prepared for the Western Canada Wait List Project.
- [191] Claudia Sanmartin, Samuel E.D. Shortt, Morris L. Barer, Sam Sheps, Steven Lewis, and Paul W. McDonald. Waiting for medical services in Canada: lots of heat, but little light. *Canadian Medical Association Journal*, 162(9):1305–1310, 2000.
- [192] Sisira Sarma and Wayne Simpson. A microeconomic analysis of Canadian health care utilization. *Health Economics*, 15:219–239, 2006.
- [193] M. W. P. Savelsbergh and M. Sol. The general pickup and delivery problem. *Transportation Science*, 29:17–29, 1995.
- [194] Alexander Schrijver. *Theory of linear and integer programming*. Wiley-Interscience Series in Discrete Mathematics. John Wiley & Sons Ltd., Chichester, 1986. A Wiley-Interscience Publication.
- [195] James P. Sethna, Karin A. Dahmen, and Christopher R. Myers. Crackling noise. *Nature*, 410:241–250, 2001.
- [196] James P. Sethna, Karin A. Dahmen, and Olga Perković. Random field Ising models of hysteresis. arXiv:cond-mat/0406320, 2005.
- [197] S. Shechter. The optimal time to initiate HIV therapy. In *INFORMS Optimization Society Conference: Optimization and Health Care*, San Antonio, Texas, February 3–5, 2006.
- [198] Brian Skyrms and Robin Pemantle. A dynamic model of social network formation. *Proceedings of the National Academy of Sciences*, 97:9340–9346, 2000.
- [199] Kaiser staff. Health care spending in the United States and OECD countries. Online, <http://www.kff.org/insurance/snapshot/index.cfm>, 2007.
- [200] StatSoft, Inc. Electronic statistics textbook. Technical report, StatSoft, Inc., Tulsa, OK, 1997.
- [201] J. A. Stein, S. A. Fox, and P. J. Murata. The influence of ethnicity, socioeconomic status, and psychological barriers on use of mammography. *Journal of Health and Social Behaviour*, 32:101–113, 1991.
- [202] Ken Stein, J. Dalziel, Andrew Walker, B. Jenkins, Alison Round, and Pam Royle. Screening for hepatitis C in genito-urinary medicine clinics: a cost utility analysis. *Journal of Hepatology*, 39(5):814–825, 2003.
- [203] Andrew Steptoe and Jane Wardle. Health behaviour, risk awareness and emotional well-being in students from Eastern Europe and Western Europe. *Social Science & Medicine*, 53(12):1621–1630, 2001.
- [204] John D. Sterman. Learning from evidence in a complex world. *American Journal of Public Health*, 96:505–514, 2006.
- [205] Andrew Street and Stephen Duckett. Are waiting lists inevitable? *Health Policy*, 36(1):1–15, 1996.
- [206] A. H. Studenmund and Henry J. Cassidy. *Using Econometrics: A practical guide*. Little, Brown and Company, 1987.
- [207] L. Tabár, B. Vitak, H.-H. T. Chen, M.-F. Yen, S. W. Duffy, and R. A. Smith. Beyond randomized controlled trials: Organized mammographic screening substantially reduces breast carcinoma mortality. *Cancer*, 91(9):1724–1731, 2001.
- [208] Antuela Tako and Stewart Robinson. Towards an empirical comparison of discrete-event simulation and system dynamics in the supply chain context. In J. Garnett, S. Brailsford, S. Robinson, and S. Taylor, editors, *Proceedings of the 2006 Operational Research Society Simulation Workshop, 28-29 March 2006*. UK Operational Research Society, 2006.
- [209] Y. W. Tan. First passage probability distributions in Markov models and the HIV incubation distribution under treatment. *Mathematical and Computer Modelling*, 19(11):53–66, 1994.
- [210] C. Tarrant, T. Stokes, and A. M. Colman. Models of the medical consultation: opportunities and limitations of a game theory perspective. *Quality and Safety in Health Care*, 13:461–466, 2004.
- [211] Gavin Turrell, Brian Oldenburg, Ingrid McGuffog, and Rebekah Dent. Socioeconomic determinants of health: towards a national research program and a policy and intervention agenda, 1999. School of Public Health, Queensland University of Technology.
- [212] UNAIDS. Report on the global HIV/AIDS epidemic 2008: executive summary. Technical report, Joint United Nations Program on HIV/AIDS, 2008.

- [213] National Research Council (U.S.). *Network Science*. National Academy Press, Washington, 2005.
- [214] M. Utley, S. Gallivan, T. Treasure, and O. Valencia. Analytical methods for calculating the capacity required to operate an effective booked admissions policy for elective inpatient services. *Health Care Management Science*, 6:97–104, 2003.
- [215] S. T. Vadaparampil, V. L. Champion, T. K. Miller, U. Menon, and C. S. Skinner. Using the health belief model to examine differences in adherence to mammography among African-American and Caucasian women. *Journal of Psychosocial Oncology*, 21(4):59–79, 2005.
- [216] Ann Van Ackere and Peter C. Smith. Towards a macro model of national health service waiting lists. *System Dynamics Review (Wiley)*, 15(3):225–252, 1999.
- [217] A. van der Waall, A. Bakhtiari, B. Ramadanović, A. Rutherford, Y. Wang, and L. Vertesi. Analysis and modelling of hip, knee and cataract surgeries in British Columbia during 2001–2008 on a health authority level. Report, The Complex Systems Modelling Group, IRMACS, SFU, April 2009. Prepared for the British Columbia Ministry of Health Services.
- [218] F. Vanden Berghen and H. Bersini. CONDOR, a new parallel, constrained extension of Powell’s UOBYQA algorithm: experimental results and comparison with the DFO algorithm. *J. Comput. Appl. Math.*, 181(1):157–175, 2005.
- [219] L. Vandenberghen and S. Boyd. Applications of semidefinite programming. In *Proceedings of the Stieltjes Workshop on High Performance Optimization Techniques (HPOPT ’96) (Delft)*, Volume 29, pages 283–299, 1999.
- [220] Lieven Vandenberghen and Stephen Boyd. Semidefinite programming. *SIAM Rev.*, 38(1):49–95, 1996.
- [221] P. W. Vaughan, E. M. Rogers, A. Signal, and R. M. Swahlele. Entertainment-education and HIV/AIDS prevention: a field experiment in Tanzania. *Journal of Health Communication*, 5(Supplement):81–100, 2000.
- [222] Jan M. H. Vissers. Health care management modelling: a process perspective. *Health Care Management Science*, 1(2):77–85, 1998.
- [223] Adam Wagstaff. Econometric studies in health economics : A survey of the British literature. *Journal of Health Economics*, 8:1–51, 1989.
- [224] A. F. Widmer. Replace hand washing with use of a waterless alcohol hand rub? *Clinical Infectious Diseases*, 31:136–143, 2000.
- [225] Rainer Winkelmann. *Econometric analysis of count data*. Springer, 2003.
- [226] E. F. Wolstenholme. Towards the definition and use of a core set of archetypal structures in system dynamics. *System Dynamics Review (Wiley)*, 19(1):7–26, 2003.
- [227] Eric Wolstenholme. A patient flow perspective of U.K. health services: exploring the case for new “intermediate care” initiatives. *System Dynamics Review (Wiley)*, 15(3):253–271, 1999.
- [228] Eric Wolstenholme. Using generic system archetypes to support thinking and modelling. *System Dynamics Review (Wiley)*, 20(4):341–356, 2004.
- [229] M. H. Wright. Direct search methods: once scorned, now respectable. In *Numerical analysis 1995 (Dundee, 1995)*, Volume 344 of *Pitman Res. Notes Math. Ser.*, pages 191–208. Longman, Harlow, 1996.
- [230] Z. Yang, E. C. Norton, and S. C. Stearns. Longevity and health care expenditures: The real reasons older people spend more. *Journal of Gerontology*, 58B(1):S2–S10, 2003.

Index

- addiction, 122
- analytic solution, 184
- ant colony algorithm, 190
- attractors, 98
- attributable risk, 66–69, 87
- average, *see also* central tendency

- bell curve, *see also*
 - probability distribution, normal
- black box, 17
- blind clinical trial, 26, 31
- branch and bound, 189
- Brownian motion, 141
- Bundle method, 187

- calculus, 97
 - multivariate, 97
- Canada Health Infoway, 29
- cellular automata, 129
- central limit theorem, 36, 55
- central tendency, 33, 35
- confidence interval, 34, 41, 43
- confounding risk factors, 70
- confounding risk factors, 70
- constraint set, 183, 185
- continuous (model), *see also*
 - model, continuous
- continuous simulation, *see also*
 - model, simulation
- cost containment, 20
- cues to action, 104

- data
 - cleaning, *see also* data, processing
 - cohort, 28
 - cross-sectional, 28
 - experimental, 25, 27
 - health record, 25, 27, 28, 31
 - logitudinal, 28
 - panel, *see also* data, longitudinal
 - processing, 17
 - self-reported, 30
 - serial, *see also* data, time series
 - survey, 25, 27, 28

 - time series, 28
- data analysis, *see also*
 - statistics, *see also* statistical analysis
- data collection, 16, 18, 49
- data error, 29
 - experimenter bias, 31
 - false positive, 32
 - implementation, 30
 - interpretation, 31
 - non-sampling, 29
 - pooling data sets, 32
 - publication bias, 27, 31
 - response rate, 31
 - sampling, 29
 - storage, 31
 - survey design, 30
- data quality, 29
- degree of separation, 34, 35
- demand-access-utilization chain, *see also*
 - influence diagram
- descriptive statistics, *see also* statistics,
 - descriptive
- differential equation, 97
- discrete (model), *see also* model, discrete
- discrete event simulation, *see also*
 - model, simulation
- disease, definition, 9, 66
- doctor-patient interaction, 19, 116, 120, 142
- dominance (in game theory), 117
- double blind, *see also* blind clinical trial
- duality theory, 186
- dual problem, 186

- edge (in graph theory), 126, 127
 - directed, 127
 - weighted, 127
- electronic health record, 29
- endogenous, 109
- epidemic model, 130
- equidispersion, 41
- equilibrium, 96, 98
- evolutionary algorithm, 189
- exact solution method, 188
- exogenous, 109

- expected value, 38, 39
- explanatory variable, *see also*
 - predictor variable
- feedback loop, 94, 102, 105, 154
- flow, 152, 154
- game theory, 113–115
- Gauss-Markov theorem, 55
- generalized impact fraction, *see also*
 - potential impact fraction
- generalized linear regression, *see also*
 - regression, generalized linear
- generalized method of moments, 60
- genetic algorithm, *see also*
 - evolutionary algorithm
- global minimum, 187
- gradient function, 119
- graph, 127
- graph theory, 98, 125
- healthcare demand
 - behavioural models, 19
 - global models, 20
 - operational models, 20
 - population models, 19
- health outcome, 65–67, 70
- health stock, 115, 119, 122
- heuristics, 189
- hierarchical linear model, 61
- human capital model, 113, 114, 119
- influence diagram, 102, 106, 107
- integer program, *see also*
 - optimization problem, integer
- integral equation, 97
- intervention
 - education-based, 82, 84, 85, 87
 - policy-based, 81, 82, 84
 - primary versus secondary, 148
- latent variables, 109
- least squares, *see also*
 - ordinary least squares
- lifetime utility function, 122
- linear regression, 58
- linear algebra, 97
- linear function, 97
- linear minimax problem, 118
- linear program, *see also*
 - optimization problem, linear
- linear regression, 58, 62
- link function, 57
- local minimum, 187
- logistic curve, 55, 59
- logistic regression, *see also*
 - regression, logistic
- Markov
 - assumption, 135, 137, 144, 145
 - chain, finite state, 136, 138, 142
 - chain, infinite state, 141
 - decision process, 141
 - order of model, 137, 139, 140
 - process, 141
 - semi-Markov process, 141
 - state space, 136
- maxi-min criterion, *see also*
 - mini-max criterion
- maximum likelihood estimation, 56, 57, 182
- MDP, *see also* Markov, decision process
- mean, 33, 35
- median, 33, 35
- mini-max criterion, 117
- mode, 33, 35
- model
 - behavioural, 101, 105, 106
 - conceptual, 16
 - continuous, 15
 - definition, 4, 8
 - deterministic, 15
 - discrete, 15
 - dynamic, 15
 - epidemiological risk, 67
 - guiding principles, 11
 - health belief, 101, 103, 107
 - hierarchical linear, 62
 - implementation, 99
 - Markov, 131, 135
 - mathematical, *see also*
 - model, quantitative
 - mover-stayer, 146
 - multi-level, *see also*
 - model, hierarchical linear
 - network, 126
 - process, 12
 - psychosocial, 19
 - psychosocial risk, 81, 107
 - qualitative, 9, 14, 94, 154
 - quantitative, 8, 14, 16, 94
 - queue, *see also* queueing theory
 - random field Ising, 132
 - simulation, 17, 99
 - continuous, 99
 - discrete event, 20, 99, 176
 - static, 15
 - statistical, 49
 - stochastic, 15
 - system dynamics, 127
 - types, 13
 - validation, 14, 17, 18
- model function, 49, 51
- mutually exclusive events, 37
- Nash equilibrium, 113, 116, 121
- network, 127
- network theory, 125
- Newton's method, 187

- node (in graph theory), 126, 127
 - degree of, 127
- normal distribution, *see also*
 - probability distribution, normal
- normal linear regression, *see also*
 - regression, normal linear
- numerical analysis, 18, 98
- objective function, 181, 183
- odds ratio, 66
- online algorithm, 191
- optimization, 18, 98, 181
 - optimal behaviour, 18
- optimization problem, 182, 184
 - combinatorial, 188
 - continuous, 184, 185
 - differentiable convex, 186
 - differentiable non-convex, 187
 - discrete, 184, 188
 - dynamic, 190
 - integer, 188, 193
 - linear, 185, 191
 - non-differentiable, 188
 - quadratic, 55, 186
 - scheduling, 191
 - semi-definite, 186
- ordinary least squares, 53, 55, 182
- overdispersion, 41
- overfitting (a model), 74, 75
- path, 126, 127
 - connected, 126, 127
- patient-doctor interaction, *see also*
 - doctor-patient interaction
- payoff function, 113, 115, 122
- payoff table, 117
- pdf, *see also* probability density function
- perceived barriers, 104
- perceived benefit, 103
- perceived efficacy, 82, 84, 104
- perceived risk, 82, 84, 87
- perceived severity, 104
- perceived susceptibility, 103
- player (in game theory), 113, 117
- potential impact fraction, 71
- potential impact fraction, 66, 67, 71, 77
- predictor variable, 49–51, 53, 55, 56, 58, 59
- prevented fraction, 66–69
- PREVENT model, 77
- primal problem, 186
- Prisoner's Dilemma, 115, 120
- probability, 33, 35, 36
- probability density function, 39, 50
- probability distribution, 34, 37
 - continuous, 38
 - empirical, 39
 - exponential, 40
 - finite, 38
 - multinomial, 39
 - negative binomial, 41
 - normal, 34, 36, 39, 55
 - Poisson, 38, 40
- probability distribution function, *see also*
 - probability density function
- psychosocial, *see also*
 - model, psychosocial risk
- publication bias, 74
- publication bias in situ, 74
- quadratic program, *see also*
 - optimization problem, quadratic
- queue, *see also* queueing theory
- queueing theory, 14, 20, 165
 - arrival pattern, 166, 168
 - arrival rate, 172, 176
 - balking, 170
 - blocking, 20, 169
 - drop-off, 170, 176
 - equilibrium state, 167, 170, 172
 - impatience, 167
 - Jackson Network, 175
 - jockeying, 170
 - length, 167
 - multistage, 169
 - reneging, 170
 - server, 165, 168
 - service channel, 166, 168
 - service pattern, 166, 168
 - system capacity, 166, 168
 - traffic model, 165–167
 - wait time, 20, 165
- queue discipline, 166, 169
 - first in first out (FIFO), 166, 176
 - last in first out (LIFO), 166
 - priority schema, 166
 - service in random order (SIRO), 166, 176
- rational addiction theory, 122, 123
- recovery curve, 61
- recovery rate, 61
- regression
 - generalized linear, 53, 56
 - logistic, 53, 55, 57, 62
 - normal linear, 53, 55, 57
- regression analysis, 50, 51
- regression coefficient, 54, 55
- relative risk, 66–69, 72
- representative agent, 114
- response variable, 49, 51, 53, 55, 56, 58, 59
- risk, definition, 9
- risk behaviour, 65, 82
- risk factor, 51, 65, 67, 69, 75, 77
- risk ratio, 66, 87
- scheduling problem, *see also*
 - optimization problem, scheduling
- self-efficacy, 104, 107

- semi-definite program, *see also*
 - optimization problem, semi-definite
- sensitivity analysis, 18
- server, *see also* queueing theory, server
- simulated annealing, 189
- simulation, *see also* model, simulation
- single blind, *see also* blind clinical trial
- SIR model, 131, 135
- six degrees of separation, 125
- small-world property, *see also*
 - six degrees of separation
- social interaction, 125, 129
- social network, 19
- standard deviation, 34, 35
- standard error, 36, 41
- state space, 136, 137
- statistical analysis, 49, 97
- statistical significance, 41
- statistics, 33, 35
 - descriptive, 33–35
 - summary, 34
- steepest descent, 186
- stock, 152, 154
- systems thinking, 151, 153, 154
- system dynamics, 151–154, 156

- tabu search, 190
- traffic models, *see also* queueing theory
- transition matrix, 141
- transition probability, 135, 137, 139, 141
- transition rate, *see also*
 - transition probability
- trend impact fraction, 77
- triple blind, *see also* blind clinical trial

- underdispersion, 41
- utility function, 113, 114, 119, 120, 122
 - expected lifetime, 122

- validation, 50
- variance, 35
- vertex (in graph theory), 126, 127

- waitlist, *see also* queueing theory
- wait time, *see also*
 - queueing theory, wait time
- Wiener process, 141

- zero sum, 117
- zero sum game, 119

How many patients will require admission to my hospital in two days? How widespread will influenza be in my community in two weeks? What will the changing demographics of our community do to affect demand for medical services in our region in two years? These and similar questions are the province of *Modelling in Healthcare*. This new volume, presented by the Complex Systems Modelling Group at Simon Fraser University in Canada, uses plain language, sophisticated mathematics and vivid examples to guide and instruct. Sage advice on the benefits and limitations of the modeling process and model predictions is generously distributed so that the reader comes away with an understanding not only of the process but also on the practical uses (and misuses!) of models. Perhaps the most important aspect of this book is that the content and the logic are readily understandable by modelers, administrators and clinicians alike. This volume will surely serve as their common and thus preferred reference for modeling in healthcare for many years.

—**Timothy G. Buchman, Ph.D., M.D., FACS, FCCM**

Modelling in Healthcare adds much-needed breadth to the curriculum, giving readers the introduction to simulation methods, network analysis, game theory, and other essential modeling techniques that are rarely touched upon by traditional statistics texts.

—**Ben Klemens, Ph.D.**

Mathematical and statistical modeling has tremendous potential for helping improve the quality and efficiency of health care delivery and as a tool for decision making by health care professionals. This book provides many relevant and successful applications of modeling in health care and can serve as an important resource and guide for those working in this exciting new field.

—**Reinhard Laubenbacher, Ph.D.**

ISBN 978-0-8218-4969-9



9 780821 849699

MBK/74



For additional information
and updates on this book, visit

www.ams.org/bookpages/mbk-74

AMS on the Web
www.ams.org