

Simulation Foundations, Methods and Applications

Series Editor

Louis G. Birta, University of Ottawa, Canada

Advisory Board

Roy E. Crosbie, California State University, Chico, USA

Tony Jakeman, Australian National University, Australia

Axel Lehmann, Universität der Bundeswehr München, Germany

Stewart Robinson, Loughborough University, UK

Andreas Tolk, Old Dominion University, USA

Bernard P. Zeigler, University of Arizona, USA

More information about this series at <http://www.springer.com/series/10128>

David J. Murray-Smith

Testing and Validation of Computer Simulation Models

Principles, Methods and Applications



Springer

David J. Murray-Smith
School of Engineering
University of Glasgow
Glasgow, UK

ISSN 2195-2817 ISSN 2195-2825 (electronic)
Simulation Foundations, Methods and Applications
ISBN 978-3-319-15098-7 ISBN 978-3-319-15099-4 (eBook)
DOI 10.1007/978-3-319-15099-4

Library of Congress Control Number: 2015953011

Springer Cham Heidelberg New York Dordrecht London
© Springer International Publishing Switzerland 2015

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media
(www.springer.com)

Preface

This book is intended to fill a gap in the currently available literature on the development and application of dynamic simulation models. It deals with issues of model quality and, more specifically, with the processes of testing, verification and validation. Since simulation models can never be proved to be “valid” in any absolute sense, the topic of model testing inevitably involves subjective issues and often a trade-off between accuracy, cost and practical issues associated with the intended application of the model. The emphasis within the book is mainly on continuous system simulation problems, and case studies are used to provide examples from the fields of engineering and physiology. The range of these applications and their cross-disciplinary nature reflects my research interests and activities over a period of almost 50 years.

Since the book is aimed at people with interests in simulation models and their use in practical applications in many different fields, some assumptions are made about the prior knowledge of the readers. Relevant supplementary material is therefore being provided through a website (<http://www.springer.com/gb/book/9783319150987>), and it is hoped that this should provide a convenient way of accessing additional background information, both in terms of the general principles of modelling and the application areas considered in the case studies. For those who do not have a background in engineering and the physical sciences, this includes sections about mathematical and system modelling concepts. Similarly, for those whose prior knowledge is lacking in terms of the biological sciences and who need more in order to understand aspects of some of the physiological case studies, the supplementary material includes sections which present some basic concepts from those areas. No attempt has been made to make the supplementary material sufficient on its own to meet the needs of everyone. Instead, only a brief account of each topic is included on the website, and links are provided to other sources of information which are far more extensive and detailed. The supplementary material also includes some data sets relating to some of the case studies, and it is hoped that these may allow readers to carry out their own investigations of those examples. Frequency-domain and time-domain data from tests carried out on some

relatively simple systems and models, which are not discussed within the book, are also provided. It is hoped that these may allow the reader to explore and apply experimental modelling and model testing methods to these additional data sets. All the data sets and models provided through the website may be used freely and shared with others, provided the source is acknowledged.

Since the case studies, and other applications discussed in the book, are drawn from research projects and my teaching activities, I must record my sincere thanks to the many research students, research assistants, undergraduate students and colleagues who contributed in important ways. Some of those receive explicit mention through references to reports, theses and journal or conference publications, but I must express my thanks to all who have contributed to the work in any way. I must also thank students who may have encountered some of these case studies within their courses and whose questions and difficulties have contributed significantly to the way in which material has been presented.

Glasgow, UK
June 2015

David J. Murray-Smith

Contents

1	An Introduction to Simulation Models and the Modelling Process	1
1.1	Objectives in Mathematical Modelling and Computer Simulation	1
1.2	Requirements Definition and Conceptual Modelling	3
1.3	Issues of Model Quality	5
1.4	Model Re-use	6
1.4.1	Model Libraries	6
1.4.2	Generic Models	7
1.5	Classes of Model	8
1.5.1	Models Involving Continuous Variables	9
1.5.2	Discrete-Event and Hybrid Models	11
1.5.3	Inverse Models and Inverse Simulation Methods	12
1.6	Interactions Between Different Types of Simulation Model and Other Software Tools	14
1.7	Organisation of the Book	14
	References	16
2	Concepts of Simulation Model Testing, Verification and Validation	19
2.1	Model Quality, Uncertainties and Errors	19
2.2	The Iterative Processes of Model Development, Testing, Improvement and Acceptance	23
2.3	The General Principles of Model Evaluation	28
2.4	Verification and Validation of Sub-models	30
2.5	Discussion	31
	References	32
3	Measures of Quality for Model Validation	35
3.1	Choice of Output Variables for Model Quality Assessment	35
3.2	Graphical Methods and Measures	36

3.3	Deterministic Quantitative Measures	39
3.3.1	Time-Domain Measures	39
3.3.2	Frequency-Domain Measures and Comparisons	43
3.4	Statistical Measures	44
3.5	Visualisation Techniques	45
3.5.1	Polar Diagrams	45
	References	47
4	Sensitivity Analysis for Model Evaluation	49
4.1	An Introduction to Sensitivity Analysis Methods	49
4.2	Sensitivity Functions	50
4.2.1	Parameter Perturbation Methods of Sensitivity Analysis	51
4.2.2	Sensitivity Analysis Through the Use of Sensitivity Models	52
4.3	Parameter Sensitivity Analysis of Linearised Continuous State-Space Models	54
4.4	Parameter Sensitivity Analysis of Continuous Transfer Function Models	55
4.5	Sensitivity Analysis and Validation of Continuous Models for Small and Large Changes in the System	56
4.6	Sensitivity Analysis of Discrete-Event and Hybrid Models	58
4.7	Discussion	59
	References	59
5	Experimental Data for Model Validation	61
5.1	An Introduction to Experimental Modelling Techniques	61
5.2	Experimental Modelling Methods and Their Role in Model Development and Validation	63
5.2.1	An Overview of System Identification and Parameter Estimation Techniques	64
5.2.2	Model Structure Optimisation	66
5.2.3	Issues of Identifiability	69
5.2.4	Design of Experiments and the Selection of Test-Input Signals	71
5.2.5	Accuracy of Estimates	74
	References	75
6	Methods of Model Verification	77
6.1	General Issues in Simulation Model Verification	77
6.1.1	Verification of Simulation Models Based on Ordinary Differential Equations and Differential Algebraic Equations	80
6.1.2	Verification of Models Based on Partial Differential Equations	81

6.1.3	Verification of Discrete-Event and Hybrid Models	81
6.2	The Role of Formal Methods in the Verification of Simulation Models	82
	References	83
7	Methods for the Invalidation/Validation of Simulation Models	85
7.1	An Introduction to Methods of Model (In)Validation	85
7.2	Quantitative Methods	86
7.2.1	Simple Methods for Predictive Validation	86
7.2.2	Methods Involving System Identification and Parameter Estimation Techniques	88
7.2.3	Barrier Certificate Methods	92
7.2.4	Methods Based on Model Distortion	92
7.2.5	Methods Based on Parameter Sensitivity Analysis	94
7.3	Face Validation	95
7.4	Approaches Based on Comparisons with Other Models	101
7.5	Data Sets for Model Testing	102
7.6	Validation of Sub-models and Generic Models	104
7.6.1	Library Sub-models	104
7.6.2	Generic Models	105
7.7	Special Issues with Distributed Parameter Models	105
7.8	Validation of Discrete-Event and Hybrid Models	106
7.9	Acceptance or Upgrading of Models	106
7.10	Discussion	107
	References	109
8	Management Issues Within Simulation Model Development and Testing	113
8.1	The Need for Management Procedures	113
8.2	Tools for the Management of Simulation Models	117
8.3	Simulation Model Documentation and the Use of Model Libraries	117
8.4	Benefits Versus Costs of Model Management Procedures	121
	References	124
9	Case Study: Development and Testing of a Simulation Model of Two Interconnected Vessels	127
9.1	Introduction to the Case Study	127
9.2	A Nonlinear Model of the Coupled-Tanks System	128
9.3	Experiments for Estimation of Parameters C_{d1} and C_{d2}	131
9.3.1	A Test for Estimation of the Discharge Coefficient C_{d1}	131
9.3.2	A Test for Estimation of the Discharge Coefficient C_{d2}	132

9.3.3	Estimation of Coefficients C_{d1} and C_{d2} from Test Results for Steady-State Conditions	133
9.4	Internal Verification of the Simulation Model	134
9.4.1	Systematic Checking of Code or Block Diagram Interconnections	134
9.4.2	Algorithmic Checks	135
9.4.3	Checks Involving Comparisons of Simulation Results with Analytical Solutions	135
9.5	Validation of the Simulation Model	136
9.5.1	Graphical Methods	137
9.5.2	Application of the Model Distortion Approach	139
9.5.3	Application of Genetic Programming (GP) Techniques	141
9.5.4	Application of the Inverse Simulation Approach	142
9.6	Possible Improvements to the Basic Model	144
	References	145
10	Case Study: Model Validation and Experiment Design for Helicopter Simulation Model Development and Applications	147
10.1	Problem Areas in Helicopter Modelling and Simulation	147
10.1.1	Quantitative Criteria for Functional Validation of Helicopter Models	148
10.1.2	Investigation of Physical Fidelity in Helicopter Simulation Models	149
10.2	System Identification and Parameter Estimation in Helicopter Modelling	150
10.2.1	Equation-Error Estimators	154
10.2.2	Output-Error Estimators	155
10.2.3	Maximum-Likelihood Estimators	156
10.3	Test Input Design for Helicopter System Identification and Model Validation	157
10.3.1	Design for a Specified Input Auto-spectrum	160
10.4	The Validation of Six-Degrees-of-Freedom Helicopter Models	165
10.5	Coupled Flapping/Inflow Models of Helicopter Rotors	170
10.6	Discussion	170
	References	172
11	Case Study: Compartmental Modelling of the Gas-Exchange Processes of the Human Lungs	175
11.1	Introduction	175
11.1.1	Modelling and Simulation Techniques in Respiratory Physiology	176

11.2	Simple Compartmental Models with Continuous Gas and Blood Flow	177
11.2.1	General Case for Gases That Are Soluble in Blood . . .	178
11.2.2	Case of Insoluble Inert Gases	180
11.2.3	Issues of Model Quality in Models with Continuous Ventilation and Perfusion	180
11.3	A Compartmental Model with Tidal Breathing	181
11.3.1	A Tidal-Ventilation Model for Carbon Dioxide	184
11.3.2	Identifiability Analysis of the Gas Exchange Model for Carbon Dioxide	186
11.3.3	Experimental Constraints for the Gas Exchange Model for Carbon Dioxide	189
11.3.4	Experimental Design and Test Signal Selection	190
11.4	An Inhomogeneous Lung Model with Tidal Ventilation	194
11.4.1	Identifiability Analysis of the Inhomogeneous Lung Model	196
11.5	Applications of Respiratory Gas-Exchange Models	196
11.6	Quality Issues in Gas-Exchange Modelling	198
	References	199
12	Case Study: Modelling of Elements of the Neuromuscular Systems Involved in Regulation of Posture and Control of Movement	203
12.1	Introduction	203
12.2	Mathematical and Computer-Based Modelling of the System	204
12.3	The Physiology of Neuromuscular Systems	205
12.4	Models of Skeletal Muscle	207
12.4.1	Development of an Experimental Model of Skeletal Muscle	208
12.4.2	Testing and Validation of the Muscle Model	211
12.4.3	Applications of the Muscle Model	215
12.5	Modelling of Other Elements of the Neuromuscular System . . .	215
12.5.1	Modelling of Signal Transmission Pathways	215
12.5.2	Modelling of Sensory Receptors	218
12.5.3	The Testing of Models of Sensory Receptors	223
12.6	Models of the Neuromuscular Control System and the Role of Simulation in the Testing of Hypotheses	224
12.6.1	Testing of Models of the Neuromuscular Control System	227
	References	228

- 13 Further Discussion 233**
 - 13.1 Principles and Practices of Model Testing: An Overview 233
 - 13.2 Strategic Issues in Modelling and Simulation
and Current Trends in Model Verification, Validation
and Accreditation 236
 - 13.3 Research and Development Opportunities in the Field
of Model Quality Assessment 240
 - 13.4 Educational Issues 241
 - 13.5 Final Remarks 242
 - References 243

- Index 245**

Abbreviations

ADC	Analogue to digital converter
AGARD	Advisory Group on Aerospace Research and Development (NATO)
AIAA	American Institute of Aeronautics and Astronautics
ANL	Argonne National Laboratory (US)
ASCI	Accelerated Strategic Computing Initiative
ASME	American Society of Mechanical Engineers
BIM	Building Infrastructure Management
CAD	Computer-aided design
CFD	Computational fluid dynamics
DAC	Digital to analogue converter
DAE	Differential algebraic equation
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Centre)
DMSO	Defense Modeling and Simulation Office (US)
DSB	Defense Science Board (US)
ESA	European Space Agency
FMI	Functional Mock-up Interface
FNS	Functional neuromuscular stimulation
FRAC	Frequency response assurance criterion
FRF	Frequency response function
GA	Genetic algorithm
GP	Gaussian process
GP	Genetic programming
ISPOR	International Society for Pharmacoeconomics and Outcomes Research
MC/DC	Modified condition/decision coverage
M&S	Modelling and simulation
M&SCO	Modeling and Simulation Coordination Office (US)
NATO	North Atlantic Treaty Organisation
NSHEB	North of Scotland Hydro-Electric Board
ODE	Ordinary differential equation

ONR	Office of Naval Research (US)
PDE	Partial differential equation
PTB	Project test bed
S3D	Ship-Smart System Design
SA	Simulated annealing
SCS	Society for Computer Simulation
SMDM	Society for Medical Decision Making
SSD	Smart-ship design
TIC	Theil's inequality coefficient
V&V	Verification and validation
VV&A	Verification, validation and accreditation
VTB	Virtual test bed