CAMBRIDGE

Cambridge University Press
978-1-107-04026-7 - Value of Information in the Earth Sciences: Integrating Spatial Modeling and Decision Analysis
Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya
Frontmatter
More information

VALUE OF INFORMATION IN THE EARTH SCIENCES

Integrating Spatial Modeling and Decision Analysis

Value of information (VOI) is a concept in decision theory for analyzing the value of obtaining additional information to solve a problem. Gathering the right kind and the right amount of information is crucial for any decision-making process. Already commonly used in medicine, economics, and finance, VOI is becoming increasingly popular with Earth scientists.

This book presents a unified framework for assessing the value of potential data gathering schemes by integrating spatial modeling and decision analysis, with a focus on the Earth sciences. The authors discuss and compare the value of imperfect versus perfect information and the value of total versus partial information, where only subsets of the data are acquired. Concepts are illustrated using a suite of quantitative tools from decision analysis, such as decision trees and influence diagrams, as well as models for continuous and discrete dependent spatial variables, including Bayesian networks, Markov random fields, Gaussian processes, and multiple-point geostatistics. Numerous examples are used to illustrate the applicability of VOI to topics such as energy, geophysics, geology, mining, and environmental science. Real datasets and MATLAB codes are also provided as online supplementary material.

Unique in its scope, this book is of interest to students, researchers, and industry professionals in the Earth and environmental sciences who use applied statistics and decision analysis techniques, and particularly to those working in petroleum, mining, and environmental geoscience.

Jo Eidsvik is Professor of Statistics at the Norwegian University of Science and Technology (NTNU), Norway, and has previous industry work experience from the Norwegian Defense Research Establishment and Statoil.

Tapan Mukerji is Associate Professor (Research) in the Department of Energy Resources Engineering and the Department of Geophysics at Stanford University. He is a co-author of *The Rock Physics Handbook* and *Quantitative Seismic Interpretation.*

Debarun Bhattacharjya is a research staff member in the Cognitive Computing Research Group at the IBM T. J. Watson Research Center, New York. He applies his expertise in decision analysis toward developing algorithms and tools for both research and consulting purposes.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-04026-7 - Value of Information in the Earth Sciences: Integrating Spatial Modeling and Decision Analysis
Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya
Frontmatter
More information

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-04026-7 - Value of Information in the Earth Sciences: Integrating Spatial Modeling and Decision Analysis
Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya
Frontmatter
More information

VALUE OF INFORMATION IN THE EARTH SCIENCES

Integrating Spatial Modeling and Decision Analysis

JO EIDSVIK, TAPAN MUKERJI, AND DEBARUN BHATTACHARJYA

CAMBRIDGE UNIVERSITY PRESS

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-04026-7 - Value of Information in the Earth Sciences: Integrating Spatial Modeling and Decision Analysis
Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya
Frontmatter
More information

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781107040267

© Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya 2015

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

First published 2015

Printed in the United Kingdom by TJ International Ltd. Padstow Cornwall

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication Data
Eidsvik, Jo, 1973–
Value of information in the earth sciences : integrating spatial modeling and decision analysis / Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya.
pages cm
Includes bibliographical references and index.
ISBN 978-1-107-04026-7 (hbk)
1. Earth sciences–Information services. 2. Geochemical prospecting. 3. Communication in science. I. Mukerji, Tapan, 1965– II. Bhattacharjya, Debarun. III. Title.
QE26.3.E35 2015
550.01'156–dc23 2015022572

ISBN 978-1-107-04026-7 Hardback

Additional resources for this publication at www.cambridge.org/eidsvik

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-04026-7 - Value of Information in the Earth Sciences: Integrating Spatial Modeling and Decision Analysis
Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya
Frontmatter
More information

Contents

Preface *page* xi
Acknowledgments xiii

1 Introduction 1
1.1 What is the value of information? 1
1.2 Motivating examples from the Earth sciences 4
1.3 Contributions of this book 9
1.4 Organization 10
1.5 Intended audience and prerequisites 10
1.6 Bibliographic notes 13

2 Statistical models and methods 14
2.1 Uncertainty quantification, information gathering, and data examples 15
2.2 Notation and probability models 22
2.2.1 Univariate probability distributions 23
2.2.2 Multivariate probability distributions 27
2.3 Conditional probability, graphical models, and Bayes' rule 32
2.3.1 Conditional probability 32
2.3.2 Graphical models 34
2.3.3 Bayesian updating from data 39
2.3.4 Examples 42
2.4 Inference of model parameters 47
2.4.1 Maximum likelihood estimation 48
2.4.2 Examples 50
2.5 Monte Carlo methods and other approximation techniques 53
2.5.1 Analysis by simulation 53
2.5.2 Solving integrals 54

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-04026-7 - Value of Information in the Earth Sciences: Integrating Spatial Modeling and Decision Analysis
Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya
Frontmatter
More information

2.5.3 Sampling methods 58
2.5.4 Example 59
2.6 Bibliographic notes 61

3 Decision analysis 64
3.1 Background 65
3.2 Decision situations: terminology and notation 68
3.2.1 Decisions, uncertainties, and values 68
3.2.2 Utilities and certain equivalent 70
3.2.3 Maximizing expected utility 74
3.2.4 Examples 75
3.3 Graphical models 77
3.3.1 Decision trees 78
3.3.2 Influence diagrams 79
3.3.3 Examples 85
3.4 Value of information 93
3.4.1 Definition 94
3.4.2 Perfect versus imperfect information 95
3.4.3 Relevant, material, and economic information 97
3.4.4 Examples 98
3.5 Bibliographic notes 104

4 Spatial modeling 106
4.1 Goals of stochastic modeling of spatial processes 107
4.2 Random fields, variograms, and covariance 110
4.3 Prediction and simulation 114
4.3.1 Spatial prediction and Kriging 114
4.3.2 Common geostatistical stochastic simulation methods 116
4.4 Gaussian models 120
4.4.1 The spatial regression model 120
4.4.2 Optimal spatial prediction: Kriging 123
4.4.3 Multivariate hierarchical spatial regression model 124
4.4.4 Examples 125
4.5 Non-Gaussian response models and hierarchical spatial models 132
4.5.1 Skew-normal models 132
4.5.2 Spatial generalized linear models 135
4.5.3 Example 136
4.6 Categorical spatial models 139
4.6.1 Indicator random variables 139
4.6.2 Truncated Gaussian and pluri-Gaussian models 140

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-04026-7 - Value of Information in the Earth Sciences: Integrating Spatial Modeling and Decision Analysis
Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya
Frontmatter
More information

4.6.3 Categorical Markov random field models 140
4.6.4 Example 144
4.7 Multiple-point geostatistics 147
4.7.1 Algorithms 147
4.7.2 Example 148
4.8 Bibliographic notes 151

5 Value of information in spatial decision situations 155
5.1 Introduction 156
5.1.1 Spatial decision situations 156
5.1.2 Information gathering in spatial decision situations 159
5.1.3 Overview of models 160
5.2 Value of information: a formulation for static models 162
5.2.1 Prior value 162
5.2.2 Posterior value 163
5.2.3 Special cases: an overview 165
5.3 Special case: low decision flexibility and decoupled value 166
5.3.1 Prior value 167
5.3.2 Posterior value 167
5.3.3 Computational notes 168
5.3.4 Example 169
5.4 Special case: high decision flexibility and decoupled value 173
5.4.1 Prior value 174
5.4.2 Posterior value 174
5.4.3 Computational notes 176
5.4.4 Examples 177
5.5 Special case: low decision flexibility and coupled value 186
5.5.1 Prior value 188
5.5.2 Posterior value 188
5.5.3 Computational notes 189
5.5.4 Example 193
5.6 Special case: high decision flexibility and coupled value 198
5.6.1 Prior value 199
5.6.2 Posterior value 199
5.6.3 Computational notes 200
5.6.4 Example 202
5.7 More complex decision situations 208
5.7.1 Generalized risk preferences 209
5.7.2 Additional constraints 209
5.7.3 Sequential decision situations 211

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-04026-7 - Value of Information in the Earth Sciences: Integrating Spatial Modeling and Decision Analysis
Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya
Frontmatter
More information

5.8 Sequential information gathering 216
5.9 Other information measures 220
5.9.1 Entropy 221
5.9.2 Prediction variance 222
5.9.3 Prediction error 225
5.10 Bibliographic notes 227

6 Earth sciences applications 229
6.1 Workflow 230
6.2 Exploration of petroleum prospects 231
6.2.1 Gotta get myself connected: Bayesian network example 233
6.2.2 Basin street blues: basin modeling example 244
6.2.3 Risky business: petroleum prospect risking example 258
6.3 Reservoir characterization from geophysical data 263
6.3.1 Black gold in a white plight: reservior characterization example 265
6.3.2 Reservoir dogs: seismic and electromagnetic data example 271
6.4 Mine planning and safety 280
6.4.1 I love rock and ore: mining oxide grade example 280
6.4.2 We will rock you: rock hazard example 285
6.5 Groundwater management 292
6.5.1 Salt water wells in my eyes: groundwater management example 292
6.6 Bibliographic notes 299

7 Problems and projects 303
7.1 Problem and tutorial hands-on projects 304
7.1.1 Problem sets 304
7.1.2 Hands-on projects 313
7.2 Hands on: exploration of petroleum prospects 319
7.2.1 Gotta get myself connected: Bayesian network example 319
7.2.2 Basin street blues: basin modeling example 321
7.2.3 Risky business: petroleum prospect risking example 322
7.3 Hands on: reservoir characterization from geophysical data 322
7.3.1 Black gold in a white plight: reservoir characterization example 322
7.3.2 Reservoir dogs: seismic and electromagnetic data example 324
7.4 Hands on: mine planning and safety 325
7.4.1 I love rock and ore: mining oxide grade example 325
7.4.2 We will rock you: rock hazard example 326

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-04026-7 - Value of Information in the Earth Sciences: Integrating Spatial Modeling and Decision Analysis
Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya
Frontmatter
More information

7.5 Hands on: groundwater management 326
7.5.1 Part I: salt water wells in my eyes – groundwater monitoring in Netica 327
7.5.2 Part II: salt water wells in my eyes – groundwater monitoring in BNT 328
Appendix: selected statistical models and sampling methods 331
Appendix A.1: Gaussian distribution 331
A.1.1 Definition and properties 331
A.1.2 Decision analysis and VOI results 337
Appendix A.2: Generalized linear models 339
A.2.1 Definition and properties 339
A.2.2 Decision analysis and VOI results 342
Appendix A.3: Markov chains and hidden Markov models 343
A.3.1 Definition and properties 343
A.3.2 Decision analysis and VOI results 348
Appendix A.4: Categorical Markov random fields 349
A.4.1 Definition and properties 349
A.4.2 Decision analysis and VOI results 355
Appendix A.5: Discrete graphs and Bayesian networks 356
A.5.1 Definition and properties 356
A.5.2 Decision analysis and VOI results 358
Appendix B: Sampling methods 359

References 365
Index 379

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-04026-7 - Value of Information in the Earth Sciences: Integrating Spatial Modeling and Decision Analysis
Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya
Frontmatter
More information

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-04026-7 - Value of Information in the Earth Sciences: Integrating Spatial Modeling and Decision Analysis
Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya
Frontmatter
More information

Preface

This book is a result of our collaboration over the past decade on addressing problems related to the value of information (VOI) in Earth sciences applications by building links between statistics, geosciences, and decision analysis. We believe that such an interdisciplinary approach will become increasingly essential for the careful stewardship of our natural resources.

Decisions related to the Earth's natural resources are often consequential, and making these decisions under uncertainty is a ubiquitous challenge. Since there is a lot at stake, it may be worthwhile for the decision maker to obtain more information before the decision is actually made – i.e., before an irrevocable allocation of resources. When faced with uncertainty, gathering the right kind and right amount of information is crucial. Today, geo-coded data are commonly purchased, processed, and interpreted to provide information about uncertain variables, such as the spatial distribution of trees in a forest, the amount of oil or gas in the subsurface, the level of groundwater in an aquifer, or the mineral content in a mine. A crucial question to answer is: how much information should one purchase, and at what price? This question is related to the well-established concept of VOI. Additional information may help to reduce the uncertainty, but if the information has no impact on the decision, then purchasing it is not economic.

A key characteristic of applying the decision theoretic notion of VOI to the Earth sciences that makes it different from other applications is the spatial aspect: spatial uncertainty, spatially distributed information, and spatial decisions. The decision theoretic formalism provides a consistent basis for relating statistical models of spatial phenomena to the decisions. This connection facilitates decision making by providing clarity of action and also fosters innovative approaches for designing spatial information-gathering schemes.

The book presents a unified framework for VOI analysis based on statistical concepts, geological and geophysical modeling, and decision analysis. Often in the Earth sciences, information is sensed remotely – for example, from geophysical surveys that provide indirect and imperfect knowledge about the spatially varying surface. How valuable is this imperfect information? We study the comparison of various kinds of practical schemes by considering the value of imperfect versus perfect information and the value of total versus

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-04026-7 - Value of Information in the Earth Sciences: Integrating Spatial Modeling and Decision Analysis
Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya
Frontmatter
More information

partial information, where only subsets of the possible data are acquired – for example, a sparse versus a spatially dense survey.

We focus on areas of our own expertise for the benefit and interest of others with similar scientific backgrounds. Throughout the book, we will discuss and reference the work of others, but we do not aim to provide an exhaustive summary of what has been done on applying VOI to other fields, such as in medicine. Applications from the Earth sciences are highlighted, and we describe the practical use of our methods and tools via a number of illustrative examples and hands-on exercises so that readers can learn the concepts by applying them.

Even though this is a specialized book, we aim to reach a diverse group of readers. The primary intended readers include scientists, engineers, graduate students, and professionals who use applied statistics and decision theoretic models in the quantitative Earth sciences. We believe that the topics will be of interest to researchers and industry professionals in different fields of the Earth sciences: energy resources, mining, groundwater, and environmental sciences. It will also be of interest to applied statisticians and decision analysts. We hope that this book will be a practitioner's guide.

The book requires some background in basic probability and statistics and mathematical calculus, as well as an interest in Earth sciences applications. Although it is not essential, it helps to know basic multivariate analysis and decision analysis or optimization. The reader must be open to learning unfamiliar topics and be able to appreciate the added value obtained from the multidisciplinary approach. If more background knowledge is needed for a particular topic, readers can consult some of the references suggested in the bibliographic notes at the end of each chapter. The chapters define the concepts using mathematics, but without going into too much detail. Additional mathematical details about the most important models and methods used in the book are provided in the appendix. The last chapter contains exercises and larger projects including data. On the website (srb.stanford.edu/VOI), we provide more background for these examples, including data and computer code.

We hope that you find this book useful!

© in this web service Cambridge University Press www.cambridge.org

CAMBRIDGE

Cambridge University Press
978-1-107-04026-7 - Value of Information in the Earth Sciences: Integrating Spatial Modeling and Decision Analysis
Jo Eidsvik, Tapan Mukerji, and Debarun Bhattacharjya
Frontmatter
More information

Acknowledgments

We would like to acknowledge the contribution of several friends, colleagues, and collaborators who have helped us in our endeavors toward the preparation and completion of this book. This includes our co-authors on various papers pertaining to value of information (VOI) in the Earth sciences: Jef Caers, Geetartha Dutta, Maren Drange-Espeland, Steinar Ellefmo, Evangelos Evangelou, Ragnar Hauge, Ketil Hokstad, Rosemary Knight, Marie Lilleborge, Gabriele Martinelli, Sara Rekstad, Javad Rezaie, Richard Sinding-Larsen, and Whitney Trainor-Guitton. We received valuable feedback on preliminary chapter drafts from Lea Deleris, Jeffrey Keisler, Gabriele Martinelli, Sameer Parakh, Deepanshu Kumar, Javad Rezaie, Ingelin Steinsland, and Ulrich Theune. We are very grateful to those who helped design and prepare creative artwork for the book: Hessam Moussavinik, Ryan Nilsen, Mamta Parakh, and Sachin Premasuthan. We are indebted to Henning Omre for laying the foundation for our NTNU–Stanford collaboration, as well as Gary Mavko and John Weyant for their encouragement on these research topics, including supporting Debarun Bhattacharjya for a few quarters during his graduate studies at Stanford University. Gary and Henning in particular planted the seeds that grew into this collaboration. Ross Shachter and Ron Howard played an important role in revealing the power of VOI. We acknowledge the long-term support from the members of the Uncertainty in Reservoir Evaluation (URE) at NTNU, the Stanford Center for Reservoir Forecasting (SCRF), and the Stanford Rock Physics and Borehole Geophysics (SRB) consortia. The Department of Energy Resources Engineering at Stanford University hosted Jo Eidsvik during his sabbatical, allowing us to finally finish the manuscript. Finally, we thank our families for their unwavering support.

© in this web service Cambridge University Press www.cambridge.org