

International Series in
Operations Research & Management Science

Fiorenzo Franceschini
Domenico A. Maisano
Luca Mastrogiacomo

Rankings and Decisions in Engineering

Conceptual and Practical Insights

Foreword by Yoram Reich



 Springer

International Series in Operations Research & Management Science

Founding Editor

Frederick S. Hillier, Stanford University, Stanford, CA, USA

Volume 319

Series Editor

Camille C. Price, Department of Computer Science, Stephen F. Austin State University, Nacogdoches, TX, USA

Editorial Board Members

Emanuele Borgonovo, Department of Decision Sciences, Bocconi University, Milan, Italy

Barry L. Nelson, Department of Industrial Engineering & Management Sciences, Northwestern University, Evanston, IL, USA

Bruce W. Patty, Veritec Solutions, Mill Valley, CA, USA

Michael Pinedo, Stern School of Business, New York University, New York, NY, USA

Robert J. Vanderbei, Princeton University, Princeton, NJ, USA

Associate Editor

Joe Zhu, Foisie Business School, Worcester Polytechnic Institute, Worcester, MA, USA

The book series **International Series in Operations Research and Management Science** encompasses the various areas of operations research and management science. Both theoretical and applied books are included. It describes current advances anywhere in the world that are at the cutting edge of the field. The series is aimed especially at researchers, advanced graduate students, and sophisticated practitioners.

The series features three types of books:

- Advanced expository books that extend and unify our understanding of particular areas.
- Research monographs that make substantial contributions to knowledge.
- Handbooks that define the new state of the art in particular areas. Each handbook will be edited by a leading authority in the area who will organize a team of experts on various aspects of the topic to write individual chapters. A handbook may emphasize expository surveys or completely new advances (either research or applications) or a combination of both.

The series emphasizes the following four areas:

Mathematical Programming: Including linear programming, integer programming, nonlinear programming, interior point methods, game theory, network optimization models, combinatorics, equilibrium programming, complementarity theory, multiobjective optimization, dynamic programming, stochastic programming, complexity theory, etc.

Applied Probability: Including queuing theory, simulation, renewal theory, Brownian motion and diffusion processes, decision analysis, Markov decision processes, reliability theory, forecasting, other stochastic processes motivated by applications, etc.

Production and Operations Management: Including inventory theory, production scheduling, capacity planning, facility location, supply chain management, distribution systems, materials requirements planning, just-in-time systems, flexible manufacturing systems, design of production lines, logistical planning, strategic issues, etc.

Applications of Operations Research and Management Science: Including telecommunications, health care, capital budgeting and finance, economics, marketing, public policy, military operations research, humanitarian relief and disaster mitigation, service operations, transportation systems, etc.

This book series is indexed in Scopus.

More information about this series at <https://link.springer.com/bookseries/6161>

Fiorenzo Franceschini • Domenico A. Maisano •
Luca Mastrogiacomo

Rankings and Decisions in Engineering

Conceptual and Practical Insights

Foreword by Yoram Reich



Springer

Fiorenzo Franceschini
Politecnico di Torino
Torino, Italy

Domenico A. Maisano
Politecnico di Torino
Torino, Italy

Luca Mastrogiacomo
Politecnico di Torino
Torino, Italy

ISSN 0884-8289

ISSN 2214-7934 (electronic)

International Series in Operations Research & Management Science

ISBN 978-3-030-89864-9

ISBN 978-3-030-89865-6 (eBook)

<https://doi.org/10.1007/978-3-030-89865-6>

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2022

This work is subject to copyright. All rights are solely and exclusively licensed 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, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG.
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

*In memory of Maria Carla “Lalla” Prandi
(1940–2020). You’ve left indelible signs of
love and mercy in your life and you’ll never be
forgotten.*

Foreword

Waking up in the morning, I ask myself what I should wear to the introductory meeting with my research sponsor, which route to use for driving to the university, and when to leave home. I select between alternative strategies to present the project to my sponsor. I make endless other choices during this day as in any other day. In some cases, I make choices intuitively, but when it comes to critical decisions, I exercise careful judgment. Different approaches would fit different contexts and decision problems and the only way to decide which approach to use and how is by making myself familiar with this variety.

Today, rankings are exercised in all spheres of life; products are ranked on Amazon and similar platforms, services such as restaurants and hotels on platforms such as TripAdvisor, and other services such as lectures or even medical treatment on different specialized platforms. We often make our daily decisions based on these rankings. Rankings and decisions permeate our lives.

When it comes to professional life, when we address serious challenges, we must rank alternatives and make decisions collectively. In engineering or other areas, we exercise them in multidisciplinary teams, speaking diverse languages, from different cultures that need to converge on a single choice.

Similar to the availability of choices to address challenges, there are also diverse methods to choose from to rank and make decisions. Invariably, the quality of our solutions to challenges depends on our ability to select appropriate methods to fit the context and needs. We need to be familiar with the theory and practice of these methods to make them useful.

Particularly due to that diversity and complexity, this book on *Rankings and Decisions in Engineering: Conceptual and Practical Insights*, by Fiorenzo Franceschini, Domenico A. Maisano, and Luca Mastrogiacomo, is an important addition to the bookshelves of professionals not only from engineering. The book starts by defining the ranking aggregation problem, making sure to deal with a variety of imperfections that exist in practice and must be addressed in real cases. This connection between theory and practice is weaved throughout the book, making it useful for practitioners also. The book then provides an important foundation by discussing measurement theory and its relation to rankings. Following this

foundation, the book presents the following methods: correlation between rankings, rankings aggregation into decisions, and the consistency of ranking aggregation methods. While the book contains many examples throughout, the authors include several thoroughly developed engineering case studies that make the conceptual material even more concrete for engineers.

Any engineering professional engaged in group rankings and decision making would find value in reading this book. I already found it.

Systems Engineering research Initiative
Tel Aviv University, Tel Aviv, Israel

Yoram Reich

Preface

Imagine that some designers individually formulate rankings of different alternative design concepts for a new product and should identify the best one collectively. Or imagine that some reliability engineers, when qualitatively assessing the severity of potential failures of a production machine, should aggregate their subjective rankings into a single collective judgment that represents them as best as possible.

These are two of the innumerable applications of the so-called *ranking aggregation* problem, which consists in aggregating multiple subjective rankings into a single collective judgment. Despite the importance of this problem in engineering, the current scientific literature is somewhat fragmented and unstructured. The practical applications are often managed borrowing methodological approaches from more traditional contexts—such as social choice/voting theory, economics, psychometrics, multiple criteria decision making/analysis—without necessarily being familiar with the scientific literature.

This fragmentation and poor structuring, together with the limited level of methodological detail, probably depends on the fact that researchers and practitioners in engineering hardly have in-depth knowledge of decision-making techniques and tools. This limitation certainly makes it challenging to choose the most appropriate methodological approaches, depending on (1) the characteristics of the practical context, (2) the information available, and (3) the desired output data.

This book tries to overcome the above limitation, addressing an audience of academics, practitioners, and technicians working in the engineering field, who do not necessarily have in-depth knowledge of decision-making problems. The aim is to deeply investigate the ranking decision problem and the related features (such as input/output data, simplification hypotheses, and practical implications) and to illustrate several methodological approaches in a structured way. The description, intended to provide a sufficiently broad overview of state of the art, is supported by pedagogical examples and real-life case studies.

Although scientifically rigorous, the formalization of problems is not too heavy in terms of mathematical technicalities, not to undermine the legibility and fluency of the entire document. On the other hand, interesting cues and bibliographical references are available for the reader who wishes to deepen technical aspects.

With this book, the authors aim to provide the reader with a selection of the most interesting, curious, and useful topics that they have developed in over twenty years of research on decision making within the engineering field. In addition to providing an organic overview of the most consolidated methodological approaches, the book illustrates innovative techniques, which could also be profitably used outside the boundaries of engineering.

The rest of the book is organized into six chapters, which are briefly described below.

Chapter 2 formally defines the ranking aggregation problem, focusing the attention on the characteristic *input* and *output* data.

Chapter 3 explores the concept of ranking from the perspective of the so-called measurement theory and its derivations.

Chapter 4 focuses on evaluating the *association/concordance* of expert rankings, referring to some established and innovative techniques from the scientific literature.

Chapter 5 illustrates in detail a selection of (consolidated and innovative) ranking aggregation techniques, analyzing their strengths and weaknesses. The description is accompanied by several pedagogical examples.

Chapter 6 describes some quantitative tools to check the degree of consistency between the collective judgment and the input data, in a practical and intuitive way.

Chapter 7 concludes the book, presenting several real-world examples of the ranking aggregation problem within engineering, with special reference to the activities of design, development, and evaluation of the quality and reliability of products, services, and manufacturing processes.

The authors wish to gratefully acknowledge the support of all colleagues and friends who have contributed to the realization of the book with stimulating suggestions and helpful comments, including Maurizio Galetto, Federico Barravecchia, and Gianfranco Genta.

Torino, Italy

Fiorenzo Franceschini
Domenico A. Maisano
Luca Mastrogiacomo

Contents

1	Introduction to Rankings and Decisions in Engineering	1
1.1	General Problem at a Glance	1
1.2	Historical Notes	6
1.2.1	Traditional Contexts	6
1.2.2	The Problem of Interest in Engineering	8
1.3	Response Modes for Data Collection	9
	References	14
2	Ranking Aggregation Problem	17
2.1	General Concepts	17
2.2	Input Data	19
2.2.1	Type of Rankings	19
2.2.2	Importance Hierarchy of Experts	27
2.3	Output Data	28
2.4	Specific Subproblems	30
	References	30
3	Rankings and Measurements	33
3.1	Introduction	33
3.2	Theory of Scales of Measurement	34
3.2.1	Nominal Scale	35
3.2.2	Ordinal Scale	36
3.2.3	Interval Scale	36
3.2.4	Ratio Scale	37
3.2.5	Comments on Stevens' Scale Types	38
3.3	Representation Theory of Measurement	38
3.4	Rankings and Measurement Theory	40
3.4.1	Notion of Rank	40
3.4.2	Ordinal and Cardinal Rankings	43
3.4.3	Rankings as Special Measurements	45
	References	46

4	Ranking Association Measures	49
4.1	Introduction	49
4.2	Spearman's Rank-Correlation Coefficient (ρ)	51
4.2.1	Definition	51
4.2.2	Practical Interpretation	53
4.2.3	Test of Significance	53
4.2.4	Example	53
4.3	Kendall's Rank-Correlation Coefficient (τ)	54
4.3.1	Definition and Practical Interpretation	56
4.3.2	Test of Significance	57
4.3.3	Example	58
4.3.4	Concluding Remarks on ρ and τ	58
4.4	Kendall's Coefficient of Concordance (W)	62
4.4.1	Example	63
4.4.2	Tied Objects	64
4.4.3	Test of Significance	65
4.5	Adapting W to Incomplete Rankings	66
4.5.1	Descriptive Parameters	67
4.5.2	Rationale of the Revised W	71
4.5.3	Examples	75
4.5.4	Final Considerations	79
	Appendix	80
	Further Data	80
	References	81
5	Ranking Aggregation Techniques	85
5.1	Taxonomy	85
5.1.1	Taxonomizing Aggregation Techniques	88
5.2	Case Study	90
5.3	Voting Theory's Rule-Based Techniques	92
5.3.1	Best of the Best	92
5.3.2	Best Two	92
5.3.3	Instant-Runoff Voting	93
5.3.4	Borda Count	95
5.3.5	Further Application Examples	96
5.4	Techniques Involving a Hierarchy of Experts	104
5.4.1	ELECTRE-II Method	105
5.4.2	Yager's Algorithm	113
5.4.3	Enhanced Yager's Algorithm	121
5.5	Distribution-Based Techniques	133
5.5.1	Thurstone's Law of Comparative Judgment	133
5.5.2	ZM _{II} Technique	141
5.6	Comparing Different Aggregation Techniques	154
	Appendix	155
	Further Example	155
	References	157

6	Consistency of Ranking Aggregation Techniques	161
6.1	Notion of Consistency	161
6.2	p Indicators	164
6.2.1	Local Consistency: p_j Indicators	165
6.2.2	Global Consistency: p , p_A , and p_B	170
6.2.3	Examples	176
6.2.4	Optimization Through p	179
6.3	$W_k^{(m+1)}$ Indicator	180
	Appendix	183
	Additional Figures	183
	References	199
7	Case Studies in Engineering	201
7.1	Introduction	201
7.2	P-FMEA for Distributed Manufacturing Processes	203
7.2.1	Methodology	206
7.2.2	Real-World Case Study (I)	207
7.2.3	Final Considerations	214
7.3	Prioritization of QFD Engineering Characteristics	214
7.3.1	Introduction to QFD	214
7.3.2	Real-World Case Study (II)	217
7.3.3	Final Considerations	218
7.4	Quality Classification with Rank-Ordered Experts	218
7.4.1	Background	218
7.4.2	Methodology and Real-World Case Study (III)	224
7.4.3	Final Remarks	226
7.5	Multi-attribute Analysis of Quality Perception	228
7.5.1	Real-World Case Study (IV)	228
7.5.2	Mapping Bivariate Ordinal Ratings into Rankings	229
7.5.3	Weighted Borda Count	231
	References	232
	Glossary	235
	Index	245