

Haiyan Xu
Keith W. Hipel
D. Marc Kilgour
Liping Fang

Conflict Resolution Using the Graph Model: Strategic Interactions in Competition and Cooperation

Studies in Systems, Decision and Control

Volume 153

Series editor

Janusz Kacprzyk, Polish Academy of Sciences, Warsaw, Poland
e-mail: kacprzyk@ibspan.waw.pl

The series “Studies in Systems, Decision and Control” (SSDC) covers both new developments and advances, as well as the state of the art, in the various areas of broadly perceived systems, decision making and control- quickly, up to date and with a high quality. The intent is to cover the theory, applications, and perspectives on the state of the art and future developments relevant to systems, decision making, control, complex processes and related areas, as embedded in the fields of engineering, computer science, physics, economics, social and life sciences, as well as the paradigms and methodologies behind them. The series contains monographs, textbooks, lecture notes and edited volumes in systems, decision making and control spanning the areas of Cyber-Physical Systems, Autonomous Systems, Sensor Networks, Control Systems, Energy Systems, Automotive Systems, Biological Systems, Vehicular Networking and Connected Vehicles, Aerospace Systems, Automation, Manufacturing, Smart Grids, Nonlinear Systems, Power Systems, Robotics, Social Systems, Economic Systems and other. Of particular value to both the contributors and the readership are the short publication timeframe and the world-wide distribution and exposure which enable both a wide and rapid dissemination of research output.

More information about this series at <http://www.springer.com/series/13304>

Haiyan Xu · Keith W. Hipel
D. Marc Kilgour · Liping Fang

Conflict Resolution Using the Graph Model: Strategic Interactions in Competition and Cooperation

 Springer

Haiyan Xu
College of Economics and Management
Nanjing University of Aeronautics and
Astronautics
Nanjing, Jiangsu
China

D. Marc Kilgour
Department of Mathematics
Wilfrid Laurier University
Waterloo, ON
Canada

and

Keith W. Hipel
Department of Systems Design Engineering
University of Waterloo
Waterloo, ON
Canada

Department of Systems Design Engineering
University of Waterloo
Waterloo, ON
Canada

and

Centre for International Governance
Innovation
Waterloo, ON
Canada

Liping Fang
Department of Mechanical
and Industrial Engineering
Ryerson University
Toronto, ON
Canada

and

Balsillie School of International Affairs
Waterloo, ON
Canada

and

Department of Systems Design Engineering
University of Waterloo
Waterloo, ON
Canada

ISSN 2198-4182

ISSN 2198-4190 (electronic)

Studies in Systems, Decision and Control

ISBN 978-3-319-77669-9

ISBN 978-3-319-77670-5 (eBook)

<https://doi.org/10.1007/978-3-319-77670-5>

Library of Congress Control Number: 2018934334

© Springer International Publishing AG, part of Springer Nature 2018

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. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Printed on acid-free paper

This Springer imprint is published by the registered company Springer International Publishing AG
part of Springer Nature

The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

To Ju, Sheila, Joan and Hong

Preface

The theory and practice of key advances in the *Graph Model for Conflict Resolution (GMCR)* are presented for strategically investigating real-world disputes arising in any field in which conflict takes place. Since humans are inherently *competitive*, GMCR can be utilized to ascertain what is the best a particular decision maker (DM) can achieve given the social constraints of a conflict in which the DM dynamically interacts with others in terms of moves and countermoves as he or she seeks to satisfy her goals or value system. When trying to negotiate a climate change agreement, for example, each nation may act according to its own self-interests in order to fare as well as possible in the short term, by reducing its greenhouse gas emissions as little as possible. However, a country may then attempt to find out whether it can do even better if it *cooperates* with other nations to reach a fair climate change deal in which each nation cuts back very significantly in its greenhouse gas emissions in order for the nations of the world to do much better in the long run and thereby avoid the extreme consequences of climate change. Accordingly, the rich range of GMCR methodologies presented in this book and elsewhere can be employed in a highly competitive situation, in which all participants are out to satisfy their own goals, to ones in which there is a high level of cooperation when it is beneficial for DMs to form coalitions.

You, our valued reader, may wish to know if this book contains information that will be useful to your understanding and capability for resolving tough disputes in your domain of interest, which may range from personal disputes within a family to international trading conflicts among corporations and nations. If you are a *researcher* in multiple participant decision-making who wishes to refine and expand basic GMCR methodologies or to employ the latest advances in conflict resolution for tackling complex conflicts within a domain such as stakeholder satisfaction in land use development and planning, then this book should be of high value to you. If you are a *teacher* in operations research, systems engineering, or an applied field of application in which conflict takes place, you may wish to use this book as a course text at the upper undergraduate or graduate levels or else as a valuable

informative reference in a course. If you are a *mentor* of students carrying out research at the Ph.D. or Master's level, or tackling tough problems involving conflict in challenging projects, you will find this book to be highly attractive for meeting your purposes. If you are a *student* studying conflict resolution and would like to investigate how nations or regions can learn from their past mistakes in order to discover how to avoid similar situations ever taking place again, such as a great depression from an economical perspective or a devastating war with a rogue nation from a military viewpoint, then the contents of this text constitute essential informative conflict resolution techniques to include in your tool kit. A doctoral student may wish to expand the basic GMCR methodologies based on gaps that he finds when systematically studying conflict in fields such as energy development, environmental engineering, water resources, and legal studies. If you are a *practitioner* or professional like a consulting engineer, urban planner, political advisor, manager, lawyer, policy analyst, or military systems engineer, this book will be compelling for you to use in resolving challenging practical problems within your professional area of expertise. For instance, as climate change intensifies and regional wars erupt, military analysts within operations research groups in defense departments will find this book to be very useful for tackling the severe security issues involved with the mass migration of affected populations, as is occurring and intensifying right now in Europe where refugees are continually arriving in increasing numbers. If you are a professional like a computer engineer or computer scientist, you may wish to utilize the basic design for a flexible decision support system (DSS) for conflict resolution put forward in this book for programming the next generation of DSSs for employment by researchers, teachers, mentors, students, and practitioners for applying the new GMCR techniques in this book to real-life situations.

To convince you, our reader, that GMCR can be actually utilized in practice for addressing challenging *real-world disputes*, examples are provided throughout the book to demonstrate how the various ideas can be applied. These applications clearly demonstrate why "good theory means good practice" and vice versa. Hence, in the very first chapter in the book, a highly controversial groundwater contamination dispute which occurred in the town of Elmira, Ontario, Canada, is employed to explain how the conflict can be modeled and analyzed using GMCR in order to gain a better understanding and strategic insights. This same environmental conflict along with others are utilized in the book to explain how various concepts are designed and work in practice.

The basic theoretical structure of GMCR and its expansions were purposefully designed to address conflicts which actually occur in reality. To accomplish this, the underlying axioms of GMCR were formulated to reflect the key characteristics of real-world conflict, thereby forming the solid foundations upon which the theoretical framework can be properly built and expanded. For example, in a conflict situation, DMs often think like a chess player in terms of *moves and countermoves*. If a particular DM is contemplating moving from the current situation to a more preferred state, the DM may wish to know the consequences of this possible move.

If, for instance, a car manufacturer decides to decrease the selling price of its cars and thereby hopefully gain greater market share, will the company's competitors also decrease the cost of buying their cars and put the particular company in a worse situation? If so, the company is better off not to lower its prices. In GMCR, different ways in which people may *behave* under conflict can be captured mathematically by what are called solution concepts or stability definitions. Furthermore, the possible moves that a DM controls can be recorded using a graph in which the scenarios or states that could occur form the vertices (nodes) while moves that the DM can make in one step are drawn as the directed arcs connecting states. Another key feature of GMCR is that only *relative preference information* is required which means that you only have to know if a DM prefers one state over another or if the states are equally preferred. Hence, if someone asks you if you would like to have a cup of coffee or tea, you may respond by saying that I prefer to have coffee, thank you, or it does not matter. You would certainly not give a quantitative response by saying that for me coffee has a utility value of 6.912 while tea is worth 2.591. A key design feature of GMCR is that only relative preference information is needed, which is fairly easy to obtain in practice and mimics the way people think about their preferences.

The foregoing fashion of directly thinking about a conflict in terms of moves and countermoves coupled with relative preferences is called the *logical form* of the game. A person can intuitively understand how a conflict can evolve and be resolved by logically explaining what can happen using moves and countermoves as DMs attempt to do the best they can in a dispute. If, for instance, from a state all of the ways in which a DM could unilaterally improve can be sanctioned by others, then this state is said to be stable for that DM according to a certain *type of behavior*. If it is not advantageous for any of the DMs to move, the state is a possible resolution or equilibrium if it is reached during the evolution of the dispute under study. For a specific conflict, providing a logical explanation of what can happen is highly appealing. However, the information contained in a graph keeping track of moves or preferences can be stored in a matrix for computational purposes. In fact, the logical interpretation of GMCR both in terms of modeling and stability calculations can be equivalently formulated using a *matrix representation*, which is also called algebraic form. When programming the engine for calculating the stability results, the matrix form is much more efficient than its logical counterpart in terms of the number of required calculations. Moreover, for theoretical purposes, it is much easier to expand GMCR when the matrix form is utilized. Therefore, throughout the book, both the logical and matrix representations of GMCR are provided for all of the advancements that are presented, which makes this book truly unique.

To appreciate the uniqueness and innate capabilities of GMCR, the connections and differences of GMCR with respect to other game theory methods are discussed in the second chapter. Moreover, the relationships of GMCR to other formal decision-making techniques developed in the fields of Operations Research, Systems Engineering and elsewhere are clearly explained. If a decision-making

methodology like GMCR is programmed as a DSS so it can be readily applied to actual disputes, the methodology becomes an *operational decision technology*. In practice, one may use a toolbox of decision technologies for addressing a complex problem like urban expansion for which GMCR could be used for investigating the strategic and controversial aspects of the project.

In actuality, everything affects everything else within and among societal and physical systems of systems. For instance, the utilization of fossil fuels in society's industrial, transportation and electricity generation systems in nations around the world releases massive quantities of carbon dioxide into the atmosphere, which is one of a number of deadly greenhouse gases causing average temperatures around the globe to increase significantly over time. This, in turn, alters the earth's climate system, creates extreme weather conditions, shrinks the area and thickness of sea ice, melts glaciers, makes ocean levels rise, and increases the acidity of oceans. These and other negative consequences of climate change on the earth's natural systems can adversely impact societal systems such as agriculture, industry and the economy as a whole, as well as the stakeholders who are part of these systems. Accordingly, it is highly intuitive and informative to envision any problem from a *system of systems perspective*. Within this vision of reality, a useful tool like GMCR can be employed to investigate the myriads of conflicts that will arise among affected parties, which for the case of climate change will surely increase in number and intensity as the climate continues to deteriorate, perhaps irreversibly.

To responsibly handle complex problems connected to climate change, the Elmira groundwater contamination problem, and other tough issues facing society, an *integrative and adaptive approach to management and governance* can be followed in a participatory fashion with stakeholders whose interests or values must be taken into account in policy design and decision-making. In this way, solutions to problems can be found which adhere to desirable systems characteristics like sustainability, fairness, and robustness. A flexible tool like GMCR can be employed to handle disputes that may arise for which the stakeholders value systems are always considered.

After putting decision-making into perspective in Chap. 2 and explaining the vital role that GMCR has to play, various conflict models are defined in Chap. 3. As explained in Chap. 3, what is called the *option form* of the game is particularly powerful as a notation for keeping track of the options or courses of actions available to each DM in a dispute and recording the possible feasible states or scenarios that could occur in the conflict. These states are then used in both the *logical form* and *matrix representation* of GMCR presented in Sects. 3.2 and 3.3, respectively. Because they reflect the underlying value system of a DM, a crucial input to a conflict model is the relative preference of the DM among the feasible states that could occur.

Subsequent to modeling a given conflict in terms of DMs, states, state transitions, and relative preferences, a stability analysis is carried out in terms of investigating moves and countermoves that could occur according to four *solution concepts* reflecting *human behavior* under conflict when determining if a state is

stable or not: Nash stability, general metarationality, symmetric metarationality, and sequential stability. Depending on the type of preference information that is available, these solution concepts are appropriately defined for both the logical and matrix representations of GMCR. Hence, the next four chapters in the book provide the stability definitions for the following types of preference information:

Chapter 4: *Simple preference* in which a given state can be more preferred, equally preferred, or less preferred to another state by a DM.

Chapter 5: *Unknown preference* in which a DM does not know the preference relationship for some pairs of states. This type of preference uncertainty is uniquely defined for employment with GMCR since it does arise in practice. In the last chapter in this book, it is mentioned that fuzzy sets, grey numbers, and probabilistic approaches to preference uncertainty have also been developed for employment with GMCR.

Chapter 6: In some situations, a DM may greatly prefer one state over another such as when environmentalists greatly prefer that an industrialist does not allow his company to significantly pollute the surrounding environment by releasing untreated wastes. This is referred to as *degree of preference* for which the degree can be taken to any level for specified pairs of states.

Chapter 7: *Hybrid preference* in which unknown and degree of preference can occur as well as simple preference.

As mentioned earlier, in addition to determining how well a given DM may fare when behaving independently, one should also determine if a DM can do even better by cooperating with others. Hence, in Chap. 8 *coalitional stabilities* are defined for the aforementioned four types of preference situations for both the logical and matrix forms of GMCR. As an important type of follow-up analysis, the possible *evolution of a conflict* from a specified starting or status quo state to a particular final state is presented for both the logical and matrix representations of GMCR in Chap. 9. In practice, one may wish to know whether a desirable state, such as a win/win resolution, can actually be reached by DMs who have under their control unilateral moves that they can select to levy.

The book concludes with the presentation of a *universal design* of future generations of DSSs for GMCR based on an internal matrix representation structure for handling the current and future expansions of GMCR in Chap. 10. These *future opportunities* include the capability of having systems engineering investigations in which inverse engineering and behavioral engine specification can be fully studied. Inverse engineering or inverse GMCR means ascertaining the preferences needed by DMs for a desirable final state to be an equilibrium. The behavioral engine problem is given the input and output to determine the type of behavior exhibited by the DMs.

So, our cherished readers, we trust that you will enjoy the exciting journey through our comprehensive book. But hang on to your hats: there will be a lot more to come in the future both in terms of *new operational methodologies* for expanding the capabilities of GMCR and also the wealth of *pressing conflicts* that have to be properly addressed right now, as well as challenging conflicts that may

arise in the future as the earth becomes a smaller and smaller place for all of us to live and prosper.

We warmly wish you, our readers, a most revealing and exciting journey through our book.

Bon voyage!

Nanjing, China
Waterloo, Canada
Waterloo, Canada
Toronto, Canada
March 2018

Haiyan Xu
Keith W. Hipel
D. Marc Kilgour
Liping Fang

Acknowledgements

The four authors of this book have had the distinct pleasure of working with one another for many years within a stimulating academic environment of friendship, collegiality, and innovation. The academic home in which they developed many of their ideas in conflict resolution, among themselves and with colleagues and students, was the Conflict Analysis Group based in the Department of Systems Design Engineering at the University of Waterloo. The authors have been privileged to work with many gifted scholars at their own universities in Canada and China as well as at many other research institutions around the globe. Accordingly, they would like to convey their deep appreciation to their colleagues and former students who executed research on topics directly connected to the theme of this book or that complemented or inspired research contained in this text. These contributions include co-authorship of research papers that form part of the content of this book, as well as the provision of timely guidance and encouragement.

Although the solid foundations for the leading-edge ideas of the Graph Model for Conflict Resolution (GMCR) contained in this text were cleverly designed and carefully constructed over three decades ago, this book focuses on advances in GMCR achieved during the past ten years, including some material appearing in print here for the first time. Research ideas from journals or other publications are of course properly referenced. Moreover, for material that comes directly from another publication, permission of the copyright holder has been obtained.

As an expression of our sincere gratitude, we would like to record here the names of our fellow researchers who are co-authors or inspirers of ideas contained in this book. In alphabetical order, they are as follows: Taha Alhindi, Yasir Aljefri, Mubarak Al-Mutairi, Motahareh Armin, Abul Bashar, Sean Bernath Walker, Michele Mei-Ting Bristow, David Bristow, Ye (Richard) Chen, Yu Chu, Aldo Dagnino, Mitali De, Jose R. del Monte, Jianfeng Ding, Niall M. Fraser, Bing (Ben) Fu, Kei Fukuyama, Masao Fukushima, Amanda Garcia, Bingfeng Ge, Mohammad Reza Ghanbarpour, Kiyoko Hagihara, Yoshimi Hagaihara, Luai Hamouda, Xueshan Han, Yu Han, Shawei (David) He, Yuhang Hou, Kaixan (Max) Hu, Takehiro Inohara, Ju Jiang, Yangzi Jiang, Monika Karnis, Moustafa Kassab, Young-Jae Kim, Yi (Ginger)

Ke, Rami Kinsara, Hanbin (Eric) Kuang, Jonathan R. D. Kuhn, Jason K. Levy, Kevin Wu Li, Xiang-Ming (Samuel) Li, Xuemei Li, Jing Ma, Kaveh Madani, Yasser Matbouli, Darren Bruno Gerrit Meister, K. D. W. Nandalal, Leilei Ni, Donald J. Noakes, Amer Obeidi, Norio Okada, Sevda Payganeh, Xiaoyong (John) Peng, Simone Philpot, the late James Radford, Jiwu Rao, Michael R. Rooks, Sara Anne Ross, J. Fernando Molina Ruibal, Hiroyuki Sakakibara, Bader Sabtan, Maiko Sakamoto, Peter Savich, Majid Sheikhmohammady, Maisa Mendonça Silva, Aihua Song, Nigel W. Stokes, West Suhanic, Hirokazu Tatano, Marcella Maia Bezerra de Araujo Urtiga, Junjie Wang, Lizhong (George) Wang, Muhong Wang, Qian Wang, Colin Williams, Saied Yousefi, Yi Xiao, Peng Xu, Jun Yang, Xian-Pei Yin, Jing (Crystal) Yu, Dao-Zhi Zeng, Jinlong (John) Zhang, Jinshuai Zhao, Shinan Zhao, Yuming (Arthur) Zhu, and Ziming Zhu.

The authors are extremely grateful for the assistance they received in the refinement, processing, and proofreading of the final version of book. Specifically, Shinan Zhao and Yi Xiao provided a great deal of timely and expeditious help in completing the book. The authors would also like to thank professionals at Springer for the expert service they rendered in the publication of the book.

The authors are indebted for financial support provided by funding agencies in China and Canada for their long-standing support of the research contained in this book. In particular, they would like to acknowledge funding from the National Natural Science Foundation of China (NSFC) (Grant Numbers 71071076, 71471087, and 61673209) as well as the Natural Sciences and Engineering Research Council (NSERC) of Canada through its Discovery and Strategic Grants programs. Over the years, the authors' home universities have also furnished research space and in-kind support.

In closing, the authors would like to express their special appreciation of their spouses and family members who provided the love and support that enabled them to blossom in their academic careers and dedicate their creative time to challenging research projects. We all agree that it was our supportive family and social environments that made the writing of this book possible.

Nanjing, China
 Waterloo, Canada
 Waterloo, Canada
 Toronto, Canada
 March 2018

Haiyan Xu
 Keith W. Hipel
 D. Marc Kilgour
 Liping Fang

Contents

1	Conflict Resolution in Practice	1
1.1	The Pervasiveness of Conflict	1
1.1.1	Pressing Conflicts Facing Society	2
1.1.2	Objectives of This Book	3
1.1.3	Audience	4
1.2	Investigating Conflict	5
1.2.1	Key Ideas	5
1.2.2	Modeling	6
1.2.3	Stability Analysis	16
1.2.4	Follow-Up Analyses	22
1.2.5	Application Approaches	24
1.2.6	Benefits	30
1.3	Journeys Through the Book	31
1.4	Problems	36
	References	37
2	Decision-Making in Perspective	43
2.1	Overview	43
2.2	Game Theory Methods: Classifications	44
2.2.1	The Evolution of Game Theory Methods	44
2.2.2	Classifying Formal Game Theory Techniques	45
2.3	Formal Decision-Making Techniques	48
2.3.1	Operations Research	49
2.3.2	Systems Engineering	54
2.3.3	Decision Support Systems	56
2.4	Conflict Resolution in Responsible Governance	58
2.4.1	System of Systems	59
2.4.2	Integrative and Adaptive Management	64

- 2.5 Important Ideas 65
- 2.6 Problems 66
- References 68
- 3 Conflict Models in Graph Form 75**
 - 3.1 Normal Form and Option Form 76
 - 3.1.1 Normal Form 76
 - 3.1.2 Option Form 80
 - 3.2 Graph Model 84
 - 3.2.1 Decision Makers 87
 - 3.2.2 States 88
 - 3.2.3 State Transitions 89
 - 3.2.4 Preferences 91
 - 3.2.5 Directed Graph 92
 - 3.3 Matrix Representation of a Graph Model 93
 - 3.3.1 Definitions from Algebraic Graph Theory 94
 - 3.3.2 A Rule of Priority to Label Colored Arcs 99
 - 3.3.3 Adjacency Matrix and Reachable List 102
 - 3.3.4 Preference Matrices 103
 - 3.3.5 Incidence Matrix and Graph Model 104
 - 3.4 Important Ideas 105
 - 3.5 Problems 105
 - References 108
- 4 Stability Definitions: Simple Preference 111**
 - 4.1 Simple Preference 112
 - 4.1.1 Reachable Lists of a Decision Maker 112
 - 4.2 Logical Representation of Stability Definitions 115
 - 4.2.1 Two Decision Maker Case 115
 - 4.2.2 Reachable Lists of a Coalition of Decision Makers 118
 - 4.2.3 n -Decision Maker Case 121
 - 4.2.4 Interrelationships Among Stability Definitions 122
 - 4.3 Matrix Representation of Stability Definitions 124
 - 4.3.1 Preference Matrices and UM and UI Matrices 124
 - 4.3.2 Two Decision Maker Case 125
 - 4.3.3 Matrices to Construct Reachable Lists
of a Coalition 132
 - 4.3.4 n -Decision Maker Case 141
 - 4.4 Computational Complexity 144
 - 4.4.1 Two Decision Maker Case 144
 - 4.4.2 n -Decision Maker Case 145
 - 4.5 Application: Elmira Conflict 146
 - 4.5.1 Procedures for Calculating Stability 147
 - 4.5.2 Analysis of Stability Results 153

- 4.6 Important Ideas 154
- 4.7 Problems 154
- References 159
- 5 Stability Definitions: Unknown Preference 161**
 - 5.1 Unknown Preference and Reachable Lists 161
 - 5.1.1 Reachable Lists of a Decision Maker 162
 - 5.2 Logical Representation of Stability Definitions Under Unknown Preference 164
 - 5.2.1 Two Decision Maker Case 164
 - 5.2.2 Reachable Lists of a Coalition 169
 - 5.2.3 Multiple Decision Maker Case 172
 - 5.2.4 Relationships Among Stabilities in the Graph Model with Preference Uncertainty 175
 - 5.3 Matrix Representation of Stability Definitions Under Unknown Preference 177
 - 5.3.1 Preference Matrices Including Uncertainty 177
 - 5.3.2 Two Decision Maker Case 178
 - 5.3.3 Reachability Matrices for a Coalition 185
 - 5.3.4 Multiple Decision Maker Case 188
 - 5.3.5 Computational Complexity 193
 - 5.4 Application: Lake Gisborne Conflict 194
 - 5.4.1 Procedures for Calculating Stability with Unknown Preference 196
 - 5.4.2 Reachability Matrices of a Coalition in the Gisborne Model 196
 - 5.4.3 Analysis of Stability Results for the Gisborne Model 197
 - 5.5 Important Ideas 199
 - 5.6 Problems 200
 - References 206
- 6 Stability Definitions: Degrees of Preference 209**
 - 6.1 Multiple Degrees of Preference 210
 - 6.1.1 Three Types of Preference 210
 - 6.1.2 Multiple Degrees of Preference 212
 - 6.2 Reachable Lists of a Decision Maker 214
 - 6.2.1 Reachable Lists for Three Degrees of Preference 214
 - 6.2.2 Reachable Lists for Multiple Degrees of Preference 215
 - 6.3 Logical Representation of Stabilities for Three Types of Preference 216
 - 6.3.1 Two Decision Maker Case 217

- 6.3.2 Reachable Lists of a Coalition of Decision Makers 221
- 6.3.3 *n*-Decision Maker Case 221
- 6.4 Logical Representation of Stabilities for Multiple Degrees of Preferences 223
 - 6.4.1 Two Decision Maker Case 223
 - 6.4.2 Reachable Lists of a Coalition of Decision Makers 229
 - 6.4.3 *n*-Decision Maker Case 230
 - 6.4.4 Interrelationship Among Stability Definitions for Multiple Degrees of Preference 234
- 6.5 Matrix Representation of Stability Definitions for Three Degrees of Preference 238
 - 6.5.1 Preference Matrices Including Strength of Preference 238
 - 6.5.2 Two Decision Maker Case 240
 - 6.5.3 Reachability Matrix Under Strength of Preference 244
 - 6.5.4 *n*-Decision Maker Case 248
- 6.6 Application: The Garrison Diversion Unit (GDU) Conflict 251
 - 6.6.1 Model of the GDU Conflict 252
 - 6.6.2 Stability Analysis Under Four-Degree Preference 254
- 6.7 Important Ideas 257
- 6.8 Problems 257
- References 259
- 7 Stability Definitions: Hybrid Preference 261**
 - 7.1 Hybrid Preference and Reachable Lists 262
 - 7.2 Logical Representation of Stability Definitions Under Hybrid Preference 263
 - 7.2.1 Two Decision Maker Case 264
 - 7.2.2 Reachable List of a Coalition of Decision Makers Under Hybrid Preference 268
 - 7.2.3 *n*-Decision Maker Case 269
 - 7.2.4 Interrelationships Among Stabilities Under Hybrid Preference 273
 - 7.3 Some Important Matrices Under Hybrid Preference 275
 - 7.3.1 Preference Matrices Including Uncertainty and Strength 275
 - 7.3.2 Reachability Matrices Under Hybrid Preference 277
 - 7.4 Matrix Representation of Stabilities Under Hybrid Preference 279
 - 7.4.1 Matrix Representation of General Stabilities 279
 - 7.4.2 Matrix Representation of Strong and Weak Stabilities 282
 - 7.5 Application 285

- 7.6 Important Ideas 288
- 7.7 Problems 289
- References 290
- 8 Coalitional Stabilities 293**
 - 8.1 Coalition Movement Definitions 294
 - 8.2 Logical Representation of Coalitional Stabilities Under Simple Preference 295
 - 8.3 Logical Representation of Coalitional Stabilities Under Unknown Preference 297
 - 8.3.1 Logical Representation of Coalitional Stabilities Indexed l 298
 - 8.4 Logical Representation of Coalitional Stabilities Under Three Degrees of Preference 300
 - 8.4.1 General Coalitional Stabilities 300
 - 8.4.2 Strong or Weak Coalitional Stabilities 302
 - 8.5 Logical Representation of Coalitional Stability with Hybrid Preference 303
 - 8.5.1 General Coalitional Stabilities with Hybrid Preference 303
 - 8.5.2 Strong Coalitional Stabilities with Hybrid Preference 305
 - 8.6 Matrix Representation of Coalitional Stability Under Simple Preference 307
 - 8.6.1 Coalitional Improvement Matrix 307
 - 8.6.2 Matrix Representation of Coalitional Stabilities 308
 - 8.7 Matrix Representation of Coalitional Stabilities Under Unknown Preference 312
 - 8.7.1 Matrix Representation of Coalitional Improvement or Uncertain Move 312
 - 8.7.2 Matrix Representation of Coalitional Stabilities Indexed l 314
 - 8.8 Matrix Representation of Coalitional Stability with Three Degrees of Preference 322
 - 8.8.1 Matrix Representation of Mild or Strong Coalitional Improvement 322
 - 8.8.2 Matrix Representation of General Coalitional Stabilities 323
 - 8.8.3 Matrix Representation of Strong Coalitional Stabilities 327
 - 8.9 Matrix Representation of Coalitional Stability with Hybrid Preference 330
 - 8.9.1 Matrix Representation of Coalitional Improvement Under Hybrid Preference 330

- 8.9.2 Matrix Representation of General Coalitional Stabilities with Hybrid Preference 332
- 8.9.3 Matrix Representation of Strong Coalitional Stabilities with Hybrid Preference 340
- 8.10 Application: Coalition Analysis for Lake Gisborne Conflict with Simple Preference 344
 - 8.10.1 Reachability Matrices in the Lake Gisborne Model. 346
 - 8.10.2 Coalitional Stability Results in the Lake Gisborne Model 347
- 8.11 Important Ideas 349
- 8.12 Problems 350
- References 351
- 9 Follow-Up Analysis: Conflict Evolution 353**
 - 9.1 Logical Representation of Conflict Evolution 354
 - 9.1.1 Simple Preference 354
 - 9.1.2 Unknown Preference 355
 - 9.1.3 Three Degrees of Preference 357
 - 9.1.4 Hybrid Preference 359
 - 9.2 Matrix Representation of Conflict Evolution Based on Adjacency Matrix 361
 - 9.2.1 t -Legal Unilateral Move Matrix Under Various Preference Structures 362
 - 9.2.2 Status Quo Matrices Under Various Preference Structures. 364
 - 9.2.3 Application: Status Quo Analysis for Elmira Conflict Under Simple Preference 366
 - 9.3 Matrix Representation of Conflict Evolution Based on Edge Consecutive Matrix 369
 - 9.3.1 Weighted Conversion Function for Finding Colored Paths 370
 - 9.3.2 Computer Implementation 377
 - 9.3.3 Procedures of Employing the Algebraic Approach Based on Edge Consecutive Matrix 385
 - 9.3.4 Applications: Analysis of Conflict Evolution Based on Edge Consecutive Matrix 386
 - 9.4 Important Ideas 397
 - 9.5 Problems 398
 - References 399
- 10 Design of a Decision Support System for Conflict Resolution 401**
 - 10.1 Decision Support Systems 402
 - 10.1.1 Introduction 402
 - 10.1.2 Existing Decision Support Systems for the Graph Model 404

- 10.2 Universal Design of a Decision Support System for the Graph Model 405
 - 10.2.1 Overall Design 405
 - 10.2.2 Input Subsystem 406
 - 10.2.3 Analysis Engine 410
 - 10.2.4 Output Subsystem 413
- 10.3 Ongoing and Future Developments in the Graph Model Methodology 414
 - 10.3.1 Ongoing Expansions of the Graph Model 415
 - 10.3.2 Expansions of Systems Investigations in Conflict Resolution 418
- 10.4 Problems 421
- References 422
- Index 427**

About the Authors



Haiyan Xu is *Professor* with the College of Economics and Management, Nanjing University of Aeronautics and Astronautics, China. She received her B.Sc. degree from Nanjing University, China, and her Master's of Mathematics and Ph.D. degree in Systems Design Engineering from the University of Waterloo in Canada. Her current research interests in Game Theory and Optimization include the development of normal algebraic techniques for conflict resolution and methods for optimization with applications in environmental management and finance. She is *recipient* of the Excellent Professor Award from the Province of Jiangsu, China.



Keith W. Hipel is *University Professor* of Systems Design Engineering at the University of Waterloo, *Officer* of the Order of Canada, former *President* of the Academy of Science (Royal Society of Canada), *Senior Fellow* of the Centre for International Governance Innovation, *Fellow* of the Balsillie School of International Affairs, and *Coordinator* of the Conflict Analysis Group at Waterloo. He is globally renowned for his interdisciplinary research in *Systems Engineering* on the development of *conflict resolution*, *multiple objective decision-making*, and *time series analysis* for addressing complex *system of systems* problems lying at the confluence of society, technology, and the environment, with applications in *water resources*, *environmental engineering*, *energy*, and *sustainable development*.



D. Marc Kilgour is *Professor* of Mathematics at Wilfrid Laurier University and *Adjunct Professor* of Systems Design Engineering at the University of Waterloo. Most of his many publications provide a mathematical analysis of multiparty decision problems. He has contributed innovative applications of game theory and related methodologies to international relations, arms control, environmental management, negotiation, arbitration, voting, fair division, and coalition formation, and pioneered the application of decision support systems to strategic conflict. He was *Co-editor* of the Springer *Handbook of Group Decision and Negotiation* (2010), *President* of the Peace Science Society in 2012–2013, and *President* of the INFORMS Section on Group Decision and Negotiation in 2014–2017.



Liping Fang is *Professor* of Mechanical and Industrial Engineering, former *Chair* of his Department, and *Associate Dean*, Undergraduate Programs and Student Affairs, Faculty of Engineering and Architectural Science at Ryerson University and *Adjunct Professor* of Systems Design Engineering at the University of Waterloo. His research interests in Industrial and Systems Engineering include conflict resolution, agent-based modeling and simulation, e-services, environmental and water resources management, and decision support systems. He is *Fellow* of the Canadian Academy of Engineering (FCAE), Institute of Electrical and Electronics Engineers (FIEEE), Engineering Institute of Canada (FEIC), and Canadian Society for Mechanical Engineering (FCSME).

Acronyms

CCA	Council of Canadian Academies
CDO	Canadian Opposition
CIUM	Coalition Improvement or Uncertain Move
CWAM	Cooperative Water Allocation Model
DBMS	Database Management System
DGMS	Dialog Generation and Management System
DM	Decision Maker
DSS	Decision Support System
GCGMR	General Coalitional General Metarationality
GCGS	General Coalitional Graph Model Stability
GCNash	General Coalitional Nash Stability
GCSEQ	General Coalitional Sequential Stability
GCSMR	General Coalitional Symmetric Metarationality
GDU	Garrison Diversion Unit
GGMR	General General Metarationality
GS	General Graph Model Stability
GHG	Greenhouse Gases
GMCR	Graph Model for Conflict Resolution
GMCR II	GMCR (Graph Model for Conflict Resolution) II
GMR	General Metarationality
GNash	General Nash Stability
GS	Graph Model Stability
GSEQ	General Sequential Stability
GSMR	General Symmetric Metarationality
GWP	Global Water Partnership
IG	Integrated Graph
INBO	International Network of Basin Organizations
INFOR	Information Systems and Operational Research
MBMS	Model-base Management System
MCDA	Multiple Criteria Decision Analysis

MRCR	Matrix Representation for Conflict Resolution
MRSC	Matrix Representation of Solution Concepts
MRSCU	Matrix Representation of Solution Concepts with Preference Uncertainty
MSUI	Mild or Strong Unilateral Improvement
MSUIUM	Mild or Strong Unilateral Improvement or Uncertain Move
OR	Operations Research
SCGS	Strong Coalitional Graph Model Stability
SCGMR	Strong Coalitional General Metarationality
SCSEQ	Strong Coalitional Sequential Stability
SCSMR	Strong Coalitional Symmetric Metarationality
SEQ	Sequential Stability
SGMR	Strong General Metarationality
SGS	Strong Graph Model Stability
SMR	Symmetric Metarationality
SoS	System of Systems
SSEQ	Strong Sequential Stability
SSMR	Strong Symmetric Metarationality
UI	Unilateral Improvement
UIUM	Unilateral Improvement or Uncertain Move
UM	Unilateral Move
USS	United States Support
UUM	Unilateral Uncertain Move
WCGMR	Weak Coalitional General Metarationality
WCGS	Weak Coalitional Graph Model Stability
WCSEQ	Weak Coalitional Sequential Stability
WCSMR	Weak Coalitional Symmetric Metarationality
WGMR	Weak General Metarationality
WGS	Weak Graph Model Stability
WSEQ	Weak Sequential Stability
WSMR	Weak Symmetric Metarationality
WWI	World War I
WWII	World War II

List of Figures

Fig. 1.1	Main steps for applying GMCR to a specific conflict.	7
Fig. 1.2	Location of the Elmira groundwater contamination dispute in Southern Ontario, Canada.	9
Fig. 1.3	An example of transitive and intransitive preferences.	15
Fig. 1.4	Integrated graph of the Elmira conflict	20
Fig. 1.5	Flow of the contents provided in the book	32
Fig. 2.1	Genealogy of formal multiple participant decision-making models	46
Fig. 2.2	Model-based decision support system for conflict resolution	57
Fig. 2.3	Systems thinking in responsible governance.	59
Fig. 2.4	Kinds of multiple participant-multiple objective systems of systems.	60
Fig. 2.5	Societal and environmental systems of systems	60
Fig. 3.1	Graph model for the sustainable development conflict	85
Fig. 3.2	Integrated graph model for the sustainable development conflict	86
Fig. 3.3	A graph model	87
Fig. 3.4	Movements from state s_1 to state s_3 for the sustainable development conflict.	90
Fig. 3.5	Integrated graph for the Elmira model	91
Fig. 3.6	Directed graphs.	93
Fig. 3.7	A directed graph and its line graph.	94
Fig. 3.8	a_k and a_h are consecutive in order $a_k a_h$	99
Fig. 3.9	The labels of edges.	101
Fig. 3.10	Labeled graph model for the sustainable development conflict	101
Fig. 3.11	Different representations of a graph model	104
Fig. 3.12	The graph model of the superpower nuclear confrontation conflict	108

Fig. 4.1 Relations among the subsets of S and the corresponding reachable lists 113

Fig. 4.2 Graph model for a two DM model 114

Fig. 4.3 Graph model with four DMs and six states 120

Fig. 4.4 Interrelationships among the solution concepts 122

Fig. 4.5 a_k incident on a_h in $IG(G)$ 135

Fig. 4.6 The arc-by-arc and the state-by-state UM paths 136

Fig. 4.7 The arc-by-arc evolutionary paths from a_1 to a_4 137

Fig. 4.8 Integrated graph model for the Elmira conflict 147

Fig. 4.9 The labeled graph for the Elmira conflict 149

Fig. 4.10 The graph model of the superpower nuclear confrontation conflict 157

Fig. 4.11 The graph model of the Rafferty-Alameda dams conflict 158

Fig. 5.1 Relations among subsets of S and reachable lists including preference uncertainty 163

Fig. 5.2 Graph model for the extended sustainable development conflict 166

Fig. 5.3 Graph model for Example 5.3 171

Fig. 5.4 Colored paths from s_1 by coalition $N \setminus \{1\}$ 172

Fig. 5.5 Relationships among four stabilities indexed l 175

Fig. 5.6 Relationships among stabilities indexed a, b, c and d 176

Fig. 5.7 Graph model for the Gisborne conflict 195

Fig. 5.8 Graph model for the BC salmon aquaculture conflict 203

Fig. 6.1 Relationships among subsets of S and reachable lists from s 214

Fig. 6.2 Graph model for the extended sustainable development conflict under three-degree preference. 219

Fig. 6.3 Nash stability at degree k for DM i 224

Fig. 6.4 GMR stability at degree k for DM i 225

Fig. 6.5 SMR stability at degree k^+ for DM i 227

Fig. 6.6 SEQ stability at degree k for DM i 228

Fig. 6.7 General metarationality at degree k for DM i 231

Fig. 6.8 Symmetric metarationality at degree k^+ for DM i 232

Fig. 6.9 Sequential stability at degree k for DM i 234

Fig. 6.10 Interrelationships among four stabilities at level k 235

Fig. 6.11 The legal sequence of UM from state s_k 237

Fig. 6.12 Graph model for the extended sustainable development conflict under three-degree preference. 245

Fig. 6.13 Garrison Diversion Unit (GDU) 252

Fig. 6.14 The integrated graph model for movement in the GDU conflict 254

Fig. 7.1 Relations among subsets of S and reachable lists including hybrid preference 263

Fig. 7.2 Interrelationships among strong GMR stabilities indexed as a, b, c and d 275

Fig. 7.3 Interrelationships among general GMR stabilities indexed as a, b, c and d 275

Fig. 7.4 Graph model for the Gisborne conflict 286

Fig. 8.1 Graph model of moves for the Lake Gisborne conflict 345

Fig. 9.1 The colored multidigraph G 376

Fig. 9.2 Transformed graphs of G 377

Fig. 9.3 The weighted colored graph for the Elmira conflict 387

Fig. 9.4 Conversion graph for finding evolutionary UM paths for the Elmira conflict 389

Fig. 9.5 Graph conversion for finding evolutionary UI paths for the Elmira conflict 390

Fig. 9.6 Evolutionary paths by UIs with status quo state s_2 391

Fig. 9.7 Conversion graph for finding the evolutionary UI paths for the Gisborne conflict 393

Fig. 9.8 Conversion graph for finding the evolutionary UIUM paths for the Gisborne conflict 394

Fig. 9.9 Transformation of the graph model for the GDU conflict 395

Fig. 9.10 The reduced graph allowing MSUIs only for the GDU conflict 396

Fig. 10.1 The framework of a general DSS 403

Fig. 10.2 The overall structure of a graph model based DSS 406

Fig. 10.3 Input subsystem 407

Fig. 10.4 Analysis engine of a graph model based DSS 410

Fig. 10.5 The output subsystem of a graph model based DSS 413

Fig. 10.6 The perspective of future development in GMCR 419

Fig. 10.7 The “black box system” of ground penetrating radar 420

List of Tables

Table 1.1	Decision makers and options in the Elmira conflict	11
Table 1.2	Feasible states for the Elmira conflict.	11
Table 1.3	Ranking of states for MoE in the Elmira conflict from most to least preferred	13
Table 1.4	Option prioritization for MoE in the Elmira conflict	14
Table 1.5	Ranking of states for the three decision makers in the Elmira conflict	14
Table 1.6	Solution concepts describing human behavior under conflict (based on Table 1 in Hipel et al. 1997).	18
Table 1.7	Evolution of the Elmira conflict from the status quo to a transitional noncooperative equilibrium and to a final cooperative coalition equilibrium	19
Table 1.8	Application areas	26
Table 1.9	Descriptions of the cases used in this book	29
Table 1.10	Key contents in the book	33
Table 2.1	Classification of decision-making models.	51
Table 2.2	Two levels of decision-making.	53
Table 3.1	2×2 game in normal form	77
Table 3.2	Sustainable development game in normal form	78
Table 3.3	Sustainable development game in option form.	82
Table 3.4	Options for the Elmira model.	88
Table 3.5	Feasible states for the Elmira model.	89
Table 3.6	Prisoners Dilemma in normal form	106
Table 3.7	The game of Chicken in normal form	106
Table 3.8	Decision makers, options and feasible states for the superpower nuclear confrontation conflict.	108
Table 4.1	Nash stability of the sustainable development game with simple preferences	116
Table 4.2	GMR stability of the sustainable development game with simple preferences	117

Table 4.3	SMR stability of the sustainable development game with simple preferences	118
Table 4.4	SEQ stability of the sustainable development game with simple preferences	118
Table 4.5	Summary of stability results for the sustainable development game with simple preferences	123
Table 4.6	The computational complexity of GMR stability using MRSC	145
Table 4.7	Options and feasible states for the Elmira model	146
Table 4.8	Stability results of the Elmira conflict	148
Table 4.9	Adjacency matrices for the Elmira conflict.	150
Table 4.10	Preference matrices for the Elmira conflict.	151
Table 4.11	Reachability matrices for the Elmira conflict	152
Table 4.12	Stability matrices for the Elmira conflict	153
Table 4.13	Diagonal entries of stability matrices for the Elmira conflict	153
Table 4.14	The airline conflict in normal form	155
Table 4.15	Decision makers, options and feasible states for the superpower nuclear confrontation conflict	157
Table 4.16	Feasible states for the Rafferty-Alameda dams conflict.	158
Table 5.1	Options and feasible states for the extended sustainable development conflict	166
Table 5.2	Stabilities indexed α of the extended sustainable development game with uncertain preference.	167
Table 5.3	Stability results of the extended sustainable development game with uncertain preference	170
Table 5.4	Preference information for the graph model shown in Fig. 5.3	172
Table 5.5	Stability matrices for two-DM conflicts with preference uncertainty	184
Table 5.6	Diagonal entries of stability matrices for the extended sustainable development game with uncertain preference.	185
Table 5.7	Options and feasible states for the Gisborne conflict	195
Table 5.8	Certain preference information for the Gisborne model	195
Table 5.9	UM reachability matrices for the Gisborne model	198
Table 5.10	UI reachability matrices for the Gisborne model	198
Table 5.11	UIUM reachability matrices for the Gisborne model	199
Table 5.12	Stability analysis of the Gisborne model	200
Table 5.13	The features of the explicit matrix method.	201
Table 5.14	DMs and options of the BC salmon aquaculture conflict	204
Table 5.15	Feasible state for the BC salmon aquaculture conflict	205
Table 5.16	Relative preference for DMs in the BC salmon aquaculture conflict	206