THE GRAPH MODEL FOR CONFLICT RESOLUTION

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Contents

Summary

The allocation, utilization, and management of the earth's resources often give rise to serious strategic conflict, typically involving multiple interest groups, each of whom may have multiple objectives and multiple possible courses of action. The graph model for conflict resolution is put forward as a comprehensive approach for systematically studying these and other real world disputes. An actual environmental conflict arising over the pollution of an underground aquifer, apparently caused by a chemical manufacturer, is used to demonstrate how this novel decision technology is

conveniently applied in practice. At the modeling stage, we can construct a formal model of the dispute under study in terms of the decision makers, the courses of action or options available to each decision maker, and the relative preferences of each of the participants with respect to the states or possible scenarios that can take place. When using the calibrated conflict model as a basis for analysis, we can employ a range of mathematical definitions of human behavior in conflict situations to determine the stability of each possible state for every decision maker, as well as the possible compromise resolutions or equilibria. Situations in which cooperation can produce a coalition that benefits its members can also be investigated. Finally, the decision support system GMCR II allows this technology to be conveniently applied to an actual conflict.

1. Introduction

A strategic conflict is a decision problem involving several interest groups or decision makers (DMs), each of which has different preferences with respect to the possible scenarios or states that could take place during the evolution of the conflict. For example, the potential settlements of a dispute over environmental pollution may be viewed differently by a manufacturer accused of causing the pollution, various levels of government, and concerned citizens groups. To provide decision support in resolving such conflicts, many formal modeling techniques have been developed. Of specific concern here is the graph model for conflict resolution (GMCR) (Fang et al., 1993; Kilgour and Hipel, 2005), an expansion and reformulation of both conflict analysis (Fraser and Hipel, 1984) and metagame analysis (Howard, 1971). To apply the graph model conveniently and expeditiously to an actual conflict, we can employ the decision support system GMCR II.

Subsequent to an overview of the theory underlying the GMCR in the next section, the overall procedure for applying the methodology to different conflict situations and the decision support system GMCR II (Hipel et al., 1977; Fang et al., 2003) are described in Section 3. Sections 5 and 6 show how the graph model can be conveniently used for modeling and analyzing, respectively, the actual groundwater contamination conflict described in Section 4.

2. Theoretical Foundations

A conflict model is a systematic structure for encapsulating the main characteristics of a strategic conflict. After formulating the model, we can employ it as a basic structure within which the possible strategic interactions among the DMs can be extensively analyzed in order to ascertain the possible compromise resolutions or equilibria. The output from this stability analysis, as well as related sensitivity analyses, can be useful to support DMs who can exercise real power in a conflict. The next two subsections outline some of the key ideas behind modeling and stability analysis, respectively.

2.1. Modeling

The GMCR technique represents a conflict as moving from state to state (the vertices of a graph) via transitions (the arcs of the graph) controlled by the DMs. One inherent advantage of the graph model is that it can incorporate *irreversible moves*, whereby a

DM can unilaterally move from state k to state q but not from q to k. Another main advantage of the graph model is its ability to describe *common moves*, in which more than one DM can cause the conflict to move from one state to another. For example, the greenhouse effect can be caused by greenhouse gases emitted from any one of many countries around the world.

A graph model for a conflict is comprised of a directed graph and a payoff function for each DM who can affect the dispute. Let $\mathbf{N} = \{1, 2, \ldots, n\}$ denote the set of DMs and $\mathbf{U} = \{1, 2, \ldots, u\}$ the set of states or possible scenarios of the conflict. A collection of finite directed graphs $D_i = (\mathbf{U}, \mathbf{A}_i)$, $i \in \mathbf{N}$, can be used to model the course of the conflict. The vertices of each graph are the possible states of the conflict and therefore the vertex set, $\mathbf{U}$, is common to all graphs. If DM i can unilaterally move (in one step) from state k to state q, there is an arc with orientation from k to q in $\mathbf{A}_i$. In Section 5, it is shown how the option form can be used conveniently to generate the states and the graphs in a model.

DM i's graph can be represented by i's reachability matrix, $\mathbf{R}_i$, which displays the unilateral moves available to DM i from each state. For $i \in \mathbf{N}$, $\mathbf{R}_i$ is the u x u matrix defined by:

$$R_i(k,q) = \begin{cases} 1 & \text{if DM } i \text{ can move (in one step) from state } k \text{ to state } q \\ 0 & \text{otherwise} \end{cases}$$

where $k \neq q$, and by convention $R_i(k,k) = 0$.

A more efficient expression of the decision possibilities of an individual DM i is her *reachable list*. For $i \in \mathbf{N}$, DM i's reachable list for state $k \in \mathbf{U}$ is the set $\mathbf{S}_i(k)$ of all states to which DM i can move (in one step) from state k. Accordingly, $S_i(k) = \{q \in \mathbf{U} : R_i(k,q) = 1\}$.

For each DM $i \in \mathbf{N}$, a payoff function $\mathrm{P}_i : \mathbf{U} \rightarrow \mathbf{R}$, where $\mathbf{R}$ is the set of real numbers, is assumed. The payoff function for DM i, P_i, measures the relative preference of states for i. Therefore, if $k,q \in \mathbf{U}$, then $P_i(k) \geq P_i(q)$ iff [if and only if] i prefers k to q, or is indifferent between k and q. When this inequality is strict for all pairs of distinct states for every DM, the conflict is called strict ordinal. Beyond the ordinal information of preference or indifference, nothing can be inferred from the value of P_i. For example, $P_i(k) > P_i(q)$ indicates that i prefers k to q, but the value of $P_i(k) - P_i(q)$ gives no meaningful information about the strength of this preference. For convenience, small positive integers are used as the values of $P_i(\cdot)$.

A unilateral improvement, UI, from a particular state for a specific DM is any preferred state to which the DM can unilaterally move. To represent unilateral improvements, DM i's reachability matrix can be used to define i's UI matrix $\mathbf{R}_i^+$, according to

$$R_i^+(k,q) = \begin{cases} 1 & \text{if } R_i(k,q) = 1 \text{ and } P_i(k) > P_i(q) \\ 0 & \text{otherwise} \end{cases}$$

Similarly, DM i's reachable list, $\mathbf{S}_i(k)$, can be replaced by $\mathbf{S}_i^+(k)$, defined by

$$\mathbf{S}_i^+(k) = \{q \in \mathbf{S}_i(k) : R_i^+(k,q) = 1\}.$$

Thus, $\mathbf{S}_i^+(k)$ is called the *unilateral improvement list* of DM i from state k.

2.2. Stability Analysis

Because the modeling stage is the problem-structuring phase of a conflict study, significant insights about the dispute are often gained even before any analysis is carried out in the next stage. The conflict model provides a formal structure within which we can study all possible strategic interactions among the DMs. The conflict is thought of as starting at a status quo state and progressing through state transitions controlled by DMs until it reaches some final state, called the resolution or outcome. The in-depth assessment of each DM's willingness to accept various possible states as resolutions is called stability analysis. In general, a given state is stable for a DM if it is not advantageous for him to move away from the state unilaterally. Additionally, a state is automatically stable for any DM who cannot move away from it. But, if a DM can move away from the state being examined, then what is required is a precise mathematical description of how the value of such a departure is to be measured. A solution concept or stability type is such a description and is therefore a sociological model of behavior in a strategic conflict. The range of solution concepts that has been defined allows many possible patterns of conflict behavior to be modeled, in order to reflect a wide variety of strategic decision styles, from cautious and conservative to prognosticative and manipulative. In *Interactive Decision Making*, Fang, Hipel, and Kilgour define (Chapter 3), mathematically compare (Chapter 5), and provide original references for the solution concepts listed in Table 1. Additionally, they demonstrate how the graph model and an associated solution concept can be equivalently expressed using extensive games that are much more complicated and hence not as well suited for practical applications (Chapter 4), but do connect the graph model to classical game theory.

The solution concepts furnished in Table 1 are developed for application to conflicts with two or more than two DMs. The first column gives the names of the solution concepts and associated acronyms, while the second contains a brief description of how each solution concept works. The last four columns provide characterizations for the solution concepts in a qualitative sense, according to the four criteria of foresight, disimprovements, knowledge of preferences, and strategic risk. Foresight refers to the extent of a DM's ability to think ahead about possible moves that could take place. A DM with high or long foresight can imagine many moves and countermoves into the future when evaluating the consequences of an initial move on his part. Notice, for instance, that in Nash stability (R), foresight is low, whereas it is very high for non-myopic stability (NM).

The *disimprovements* criterion in the fourth column refers to a DM's willingness to move to a worse state. Moving (temporarily) in order to reach a more preferred state eventually is a strategic disimprovement. Disimprovements by opponents are moves by the other DMs to put themselves in worse positions in order to block UIs by the given

DM. The *knowledge of preferences* column refers to the preference information used in a stability analysis. For example, in a stability analysis under R (rationality or Nash), general metarationality (GMR), or symmetric metarationality (SMR), the preferences of all other DMs are not used, although their abilities to move to other states are taken into account. These solution concepts can be quite useful in situations where a DM is uncertain about the preferences of his competitors. As pointed out in the strategic risk column in Table 1, a DM who follows GMR or SMR is risk averse and conservative, and hence avoids strategic risk. When a DM adheres to Nash stability and a state is stable for her, she has no available UIs and hence ignores strategic risk.

Solution Concepts	**Stability Descriptions**	**Foresight**	**Disimprove-ments**	**Knowledge of Preferences**	**Strategic Risk**
Nash Stability (R)	DM cannot unilaterally move to a more preferred state	Low	Never	Own	Ignores risk
General meta-rationality (GMR)	All of DM's unilateral improvements are sanctioned by subsequent unilateral moves by others	Medium	By opponents	Own	Avoids risk; con-servative
Symmetric meta-rationality (SMR)	All of DM's unilateral improvements are still sanctioned even after a possible response by the original DM to sanctioning	Medium	By opponents	Own	
Sequential stability (SEQ)	All of DM's unilateral improvements are sanctioned by subsequent unilateral improvements by others	Medium	Never	All	Takes some risks; satisfices
Limited-move stability (L_h)	Each DM is assumed to act optimally within a specified number (h) of state transitions	Variable	Strategic	All	Accepts risk; strategizes
Non-myopic stability (NM)	Limiting case of limited-move stability as the number of state transitions increases to infinity	High	Strategic	All	

Source: L. Fang, K.W. Hipel, and D.M. Kilgour, *Interactive Decision Making: The Graph Model for*

Conflict Resolution (New York: Wiley, 1993)

Table 1. Solution concepts and human behavior
(*Source*: Fang et al. (1993) and Kilgour and Hipel (2005))

Because the sequential stability (SEQ) solution concept has medium foresight, it allows no disimprovements for strategic purposes; preferences of all the DMs involved are taken into account in the stability calculations. A DM who thinks according to SEQ accepts some strategic risk in searching for “satisficing” solutions, since she assumes that any improvement may be selected—individuals do not necessarily find the greatest improvement. Because limited move stability (L_h) and NM permit strategic disimprovements that will ultimately allow a DM to end up at a more favorable state, these stability types include strategic risk. Under L_h, the horizon, *h*, refers to the length of the sequence of moves that a DM can envision, beginning at the state being studied for stability. In fact, L_1 is equivalent to R and NM is the limit of L_h when *h* approaches infinity.

When analyzing for a particular stability type, we examine every state for stability of that type for each DM. A state that is stable for every DM constitutes a possible *resolution*, or *equilibrium*, of the conflict model. Naturally, the appropriate kind of stability may be the same for each DM or it may be different. When an equilibrium state is reached, the conflict may have several equilibria, and it may be to the advantage of a DM to know how to move toward the one he prefers. However, the problem is complicated by the fact that the stability types of other DMs may not be known for certain. Hence, it is useful to have stability information for a range of stability types for each DM, in order to identify more robust courses of action. Whatever the case, the stability results can be used to trace a path from the status quo state to a final outcome.

3. Applying the Graph Model to Real World Conflict

3.1. Conflict Situations

The GMCR methodology can be used in a variety of ways for systematically studying actual conflict situations, including:

- As *an analysis tool for a participant in a conflict, or an agent of a participant.* Strategic interactions following the focal participant’s actions can be analyzed, and the consequences of each action estimated, in order to improve the participant’s understanding of her position. The participant can use the graph model to make assessments and preparations as often as necessary while the conflict unfolds.
- As *a communication and analysis tool for a mediator.* The mediator can utilize the graph model methodology by using various preference rankings, without revealing (or knowing) which one correctly describes the participants, to estimate possible outcomes. This might identify options that are detrimental, irrelevant, or beneficial to all parties.
- As *an analysis tool for a third party analyst.* The analyst can use the graph model to study the evolution of the conflict and to estimate what preferences could have caused the observed outcome. The analyst can also study how the structure of the

conflict influenced behavior, thereby learning better ways to regulate future conflicts.

The next subsection summarizes the overall procedure for applying the graph model to a specific conflict situation. Section 3.3 describes the decision support system GMCR II, which can be used for conveniently implementing this procedure in practice and carrying out extensive sensitivity analyses to answer "what if?" questions. The methodology is ideally designed for studying ongoing current disputes in order to improve the decision-making process. However, it is also well suited for investigating historical disputes to explain why a conflict ended up at a specific result and to learn how better outcomes can be achieved for similar disputes that occur in the future. Often, disputes fall into simplified categories of conflict such as prisoner's dilemma, chicken, or the sustainable development game presented in the theme article entitled ***Conflict Resolution***. The graph model can also shed new light on these interesting, yet hypothetical, conflicts.

3.2. Overall Procedure for Applying the Graph Model for Conflict Resolution

Figure 1 depicts the general procedure for applying the GMCR methodology to an actual conflict.

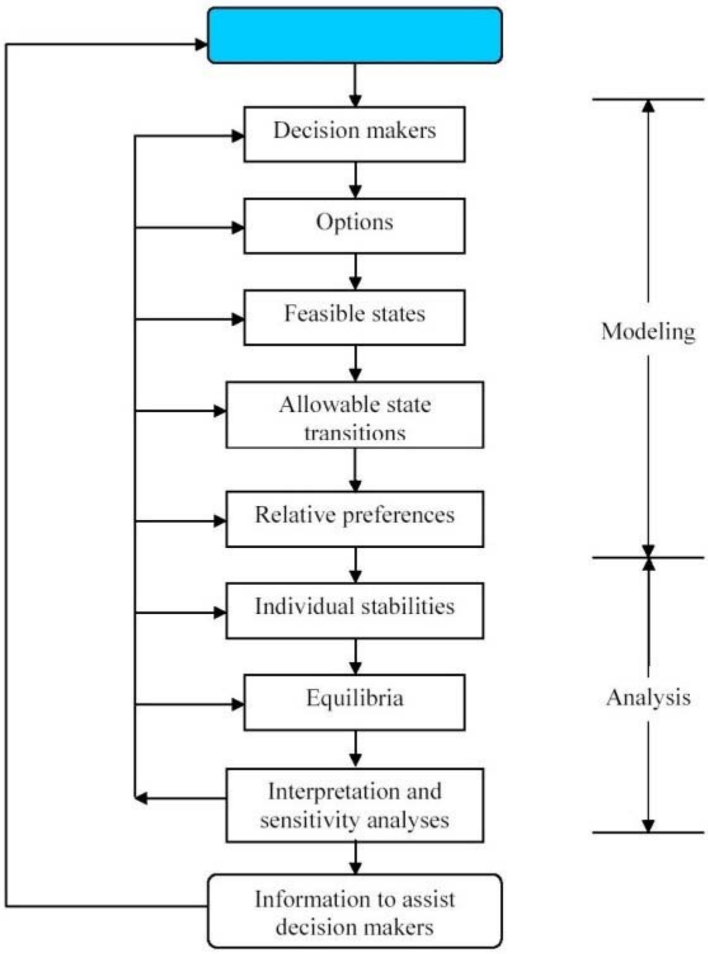

Figure 1. Applying the graph model for conflict resolution

Initially, a real-world dispute may appear to be confusing and difficult to comprehend. Nonetheless, by systematically applying in an iterative fashion the modeling and analysis stages explained in Sections 2.1 and 2.2, respectively, and shown in Figure 1, even a very complex conflict can be understood and analyzed in terms of its essential characteristics and possible resolutions.

The findings from the stability analysis stage can be interpreted by analysts, actual DMs, or interested parties in terms of the real-world conflict. The feedback arrows in Figure 1 indicate that the procedure for applying the GMCR is carried out in an iterative fashion. Whenever new insights or information are found during modeling and analysis stages, we can return to the appropriate location to make any required changes before continuing with the study.

In *sensitivity analyses*, changes in the model parameters are made systematically to assess the robustness of the stability results. In other words, sensitivity analyses are used to answer "what if?" questions. Which sensitivity analyses are appropriate is usually dictated by the specific problem being studied.

For example, when we are not completely certain of the preferences of one of the DMs, we can analyze a reasonable range of possible preference rankings to determine if and how the equilibria are affected. If the equilibria do not change after preference ranking is modified, then the equilibrium results are robust with respect to those preferences and we can have greater confidence in them. On the other hand, when the equilibria change dramatically after small preference changes, then we should make sure that the most reliable preference information is included.

Another type of sensitivity analysis is the consideration of possible coalitions among DMs, who may decide to join forces in order to benefit members of the coalition (Kilgour et al., 2001; Inohara and Hipel, 2008). An illustration of coalition analysis is given in Section 6.2 with the groundwater pollution problem introduced in Section 4 and systematically studied in Sections 5 and 6.

In fact, a sensible way to execute a strategic analysis is to first carry out standard stability analysis in which a given DM tries to see the best that he or she can do within the societal constraints of the dispute and, secondly, to ascertain if the DM can do even better by cooperating with others via joining a coalition. Additionally, when there are potential misunderstandings by one or more DMs involved in a dispute, we can employ the hypergame procedure described by Wang and Hipel to ascertain how they can influence the evolution of the conflict and its eventual resolution **(see *Misperceptions and Hypergame Models of Conflict*)**. Other factors that can be entertained when employing the graph model include the determination of the consequences of attitudes (Inohara et al., 2007), uncertain preferences (Li et al., 2004), strength of preference (Hamouda et al., 2006), fuzzy preferences (Al-Mutairi et al., 2008), and any reasonable combination of the aforementioned factors upon the potential resolutions and evolution of a conflict (Li et al., 2005). Kilgour and Hipel (2005) provide a summary of these developments, along with a reference list, as well as other research opportunities for expanding the applicability of the graph model.

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Biographical Sketches

Keith W. Hipel is University Professor of systems design engineering at the University of Waterloo, Waterloo, Ontario, Canada, where he is the Director of the Conflict Analysis Group. Dr. Hipel thoroughly enjoys teaching and is a recipient of the Distinguished Teacher Award and the Award of Excellence in Graduate Supervision from the University of Waterloo. His major research interests are the development and application of conflict resolution, multiple objective decision making, and time series analysis techniques from a systems design engineering perspective. The main application areas of these decision technologies are water resources management, hydrology, environmental engineering, and sustainable development. Dr. Hipel is an author or co-author of four books, eleven edited books and close to 200 journal papers. He is a fellow of the Royal Society of Canada (FRSC), Canadian Academy of Engineering (FCAE), Institute of Electrical and Electronics Engineers (FIEEE), International Council on Systems Engineering (FINCOSE), Engineering Institute of Canada (FEIC), and American Water Resources Association (FAWRA). Dr. Hipel is also a recipient of the Norbert Wiener Award from the IEEE Systems, Man and Cybernetics (SMC) Society, Outstanding Contribution Award from the IEEE SMC Society, title of Docteur Honoris Causa from École Centrale de Lille, W.R. Boggess Award from AWRA, and University of Waterloo Award for Excellence in Research, and was a holder of the Canada Council Killam Research Fellowship, Monbusho Kyoto University Visiting Professor Poisiton, Stanley Vineberg Memorial Visiting Professorship, Centre National de la Recherche Scientifique (CNRS) Research Fellowship and Japan Society for Promotion of Science (JSPS) Fellowship. Moreover, he is a Professional Engineer (PEng) and has carried out consulting activities with engineering firms, government agencies, and utilities in many countries. Finally, he is Vice President of the Canadian Academy of Sciences (2007-2009) and an associate editor of eight international journals including the *IEEE Transactions on Systems, Man and Cybernetics*, as well as *Group Decision and Negotiation*.

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