A Systems Engineering Approach to Conflict Resolution

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ABSTRACT

The overall objectives of this paper are to put the theory and practice of conflict resolution into proper perspective and to introduce the Graph Model for Conflict Resolution as a flexible decision technology for systematically studying realworld conflicts which can arise in engineering, international politics, business, and many other fields. Specific challenges that had to be overcome in the development of the graph model are described and it is explained how ideas from computational engineering and elsewhere were used to conquer them. For example, a difficult hurdle to overcome in the design of any decision model is how to obtain preference information. Accordingly, within the graph model paradigm for conflict resolutions a number of flexible procedures have been designed for conveniently eliciting ordinal preference information for each of the decision makers. Other algorithmic and computational difficulties that had to be surmounted included developing techniques for handling very large conflicts, modeling irreversible moves by decision makers and carefully defining solution concepts for mathematically describing a rich range of human behavior that can take place under conditions of conflict. The foregoing and other related developments have been incorporated into the decision support system GMCR II which permits practitioners and researchers to carry out comprehensive strategic studies within a user-friendly windows operating environment. The Cuban Missile Crisis of 1962 is employed for clearly demonstrating how GMCR II can be effectively used for modeling, analyzing and better understanding realworld conflict.

1. THE PERVASIVENESS OF CONFLICT

Conflict, ranging from outright warfare and stiff competition to highly cooperative situations, forms the building blocks of cultures, societies and nations. Consider, for example, the fascinating character and culture of the remarkable country called Tunisia, which have been forged into fine tempered steel through a long history of conflict, conquest and deep intellectual activity. The most famous citizen to be bred and nurtured by the sacred soil and soul of Tunisia, and one the most respected military and political leaders throughout history, was a fascinating individual named Hannibal [Lamb, 1958]. In his historical roles as the greatest general and statesman of ancient Carthage, Hannibal led his nation through its most spectacular triumphs and its lowest ebbs. Of particular historical importance was the stunning military performance of Hannibal during the second Punic war between Carthage and Rome which began in 218 B.C. Starting from Carthaginian colonies in Spain with about 60,000 troops, thousands of horses and even a herd of elephants, Hannibal crossed the Pyrenees, Southern France and the Alps, and eventually reached the Po Valley in Northern Italy where he recruited Gauls into his army. Following defeats of the Roman armies at the Trebia River and later Lake Trasimento, in 216 BC, Hannibal found his army to be far outnumbered by the Romans at Cannae in Southern Italy. However, the Carthaginians managed to encircle the Roman army and subsequently slayed about 50,000 Roman soldiers in a single day – the worst defeat ever suffered by a Roman army. Although Hannibal was finally beaten by the Roman general Scripio at Zama in Northern Africa in 202 BC, the spirit and genius of the finest of Tunisia's sons will live on in posterity.

After the fall of Carthage in 146 B.C., the Romans ruled Tunisia for 600 years, followed by the Vandals and Byzantines. The conquest of Northern Africa by the Arab invasion of the mid-seventh century brought an Arabic/Islamic culture to Tunisia which presently still forms the solid cultural and religious foundations of Tunisia. In fact, Okba Ibn Nefaa founded the first mosque in North Africa at Kairouan in Tunisia. Starting in 1574, Tunisia came under the control of the Ottoman Empire for almost three and one half centuries and later became a protectorate of France before gaining full independence in 1956. In spite of, or perhaps because of, its turbulent history, Tunisia has matured into an oasis of relative peace and prosperity that is surrounded by regimes where the sandstorms of conflict and change still persist.

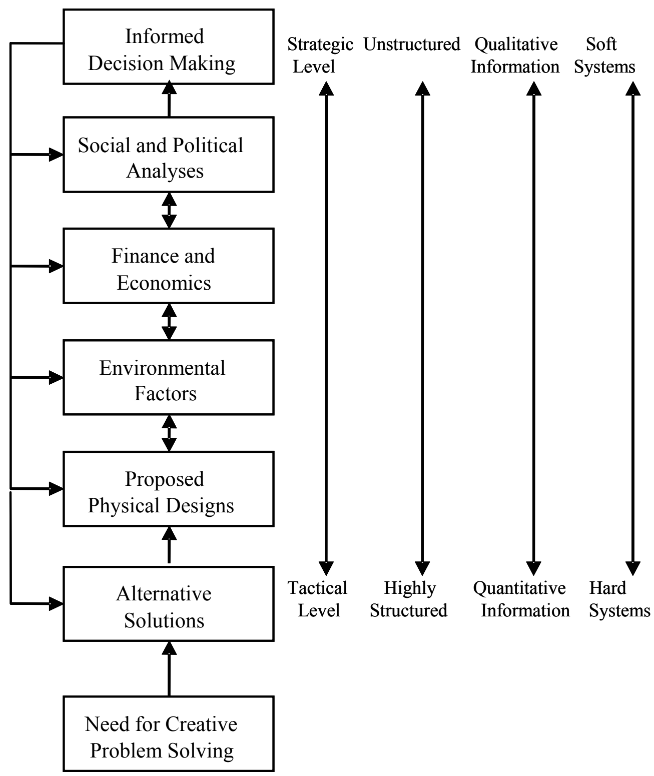
One may ask what does conflict within and among nations and cultures have to do within the modern concept of Science, Engineering and Technology (SET), let alone developments in the field of systems engineering? The answer to this question is quite simple – everything. In fact, some people have argued that many of the greatest technical advances by civilization have been made as a direct result of either warfare or the "publish or perish" syndrome of researchers employed at universities and laboratories who are in stiff competition with one another at the national and international levels. Whether working individually or cooperatively within a research team, scientists and engineers are often in a tight race with other groups in devising, testing and improving hypotheses according to the scientific method in order to be the first to arrive at clever solutions to pressing problems in both pure and applied science. For example, Allied scientists working on the Manhattan project in the United States towards the end of World War II, were the first to develop the atomic bomb which consequently brought a swift and dramatic termination to the war in the Pacific theatre. Today, research teams located around the world are trying to be the first to develop a cure for, or at least an effective vaccine against AIDS. Within in the genome field, scientists and engineers are working for corporations that are participating in a tight race to be the first to discover new genes which can be patented for the purpose of reaping potential profits by finding cures for diseases and selling associated pharmaceutical products. Indeed, in almost all areas of SET, especially those in the so-called "high tech" fields, intellectual and commercial 'warfare' are flourishing.

Consider how conflict enters the realm of engineering decision making when designing or operating a large-scale engineering project to meet specified needs of society. Exhibit 1, which is based on similar figures given by Hipel [1992] and Hipel et al. [1999], depicts a systems design approach to decision making in engineering. Imagine, for example, that one would like to design a system of reservoirs for meeting the multiple objectives of various interest groups. The flow chart on the left contains the main factors that must be considered for selecting a suitable design. Besides a sound physical design, any alternative solution must be assessed with respect to environmental, economical and financial, as well as political and social feasibilities. To assist in these evaluations, appropriate techniques from systems engineering and operational research can be employed throughout the decision making process. For instance, stochastic sequences simulated using times series models fitted to the historical river flows combined with nonlinear programming, could be employed for finding optimal physical designs that satisfy weighted multiple objectives subject to environmental, economic and financial constraints [Hipel and McLeod, 1994]. The political and social viability of various solutions can be assessed by using a technique such as the graph model for conflict resolution [Fang et al., 1993] and its associated Decision Support System, GMCR II [Hipel et al., 1997, Fang et al., 2003a, b]. The top cell on the left in Exhibit 1 indicates that output from all of the analyses provides information to assist decision makers in making an eventual overall decision. As shown by the feedback arrows on the far left in Exhibit 1, additional studies can be carried out as required to obtain a better understanding of the problem. Moreover, the decision making procedure of Exhibit 1 is not restricted to design but could also be used, for instance, to develop improved operating rules for an existing system.

The right hand portion of Exhibit 1 depicts the characteristics that are embodied in the hierarchical framework of the decision making process. Notice that as one goes from the tactical level of decision making to the strategic level, the problem changes from being highly structured and quantitative to being unstructured and qualitative. Hence, the overall problem contains both hard and soft systems components. Because of these and other factors, one must select an appropriate set of systems tools to investigate all relevant aspects of the systems being studied. To compare alternative solutions to a problem that are evaluated according to both nonquantitative and quantitative criteria from one decision maker's viewpoint, one can utilize an appropriate multiple criteria decision making technique (See, for instance, Roy [1996], Hipel [1992], Hipel et al. [1999], Hobbs and Meier [2000] and Belton and Stewart [2002] and references contained therein.). When modelling strategic interactions among decision makers, especially at the strategic level where information tends to be unstructured and more qualitative, one can employ the graph model for conflict resolution [Fang et al., 1993]. By properly addressing all key aspects of decision making, society can arrive at decisions that are more equitable to all parties involved and fall within a sustainable development framework. Moreover, when both the rich variety of physical and societal systems models reflected in Exhibit 1 are implemented as decision support systems [Sage, 1991], the resulting toolbox of decision support systems can be immediately employed for addressing complex systems engineering problems arising in water resources management [Hipel et al., 2002], industry , warfare, politics, environmental engineering and elsewhere.

Because controversies and differences of opinion are so pervasive within the realm of human decision making, there is a great need for having flexible decision technologies to assist in the modelling, analyzing, understanding and management of strategic conflict. Accordingly, the main objective of this paper is to present an overview of the graph model for conflict resolution as a comprehensive systems engineering approach for rigorously studying actual conflict. An intriguing international political confrontation – the Cuban Missile Crisis of 1962, is employed as a realworld example for illustrating how the decision support system GMCR II [Hipel et al., 1997; Fang et al., 2003a,b] permits the graph model methodology to be conveniently and expeditiously applied in practice. As a result of the decisive and wise leadership exercised by President John F. Kennedy of the United States of America during this very serious conflict, which had the potential to escalate into thermonuclear war between the two super powers, President Kennedy is worthy of being compared to other great leaders of history, including Hannibal of Tunisia. Documented applications of the graph model methodology to realworld conflict arising in a range of different fields, including aquaculture [Noakes et al., 2003], international trade [Hipel et al., 2001] and bulk water exports [Obeidi et al., 2002] are available in the published literature.

Exhibit 1. Decision Making in Engineering (Based on Hipel [1992] and Hipel et al., [1999]).



2. THE CUBAN MISSLE CRISIS

From January 21 to 25, 1998, Pope John Paul II paid an official state visit to Cuba as the guest of Premier Fidel Castro. Even though Cuba is located a mere 150 km off the America mainland, Premier Castro possessed the resilience and charisma to single-handedly rule his totalitarian communist state for almost four decades. From the cessation of the Spanish American War in 1898 until 1957, Cuba had been under the economic and political control of the United States. The corrupt government of Fulgencio Batista was subservient to US interests and many American companies possessed substantial investments in agriculture and tourism. In late 1956, a revolution to overthrow the Batista regime was initiated by Fidel Castro, an educated middle class socialist. The conquest of Cuba by Castro in 1959 resulted in the nationalization of all American property in Cuba and, hence, the Americans still have in place a trade embargo of Cuba. Following the revolution, Castro established close political, military and economic relationships with the Union of the Soviet Socialist Republics (USSR), America's mighty adversary during the infamous Cold War that emerged from the ashes of World War II and lasted until November 9, 1989.

The United States was appalled by the confiscation of American property in Cuba and the perception of a communist military threat so close to home. This culminated in the ill-advised American-sponsored Bay of Pigs invasion in April 1961, in which Cuban exiles attempted to gain a foothold in Cuba. However, the invaders were quickly routed because of poor intelligence, the lack of proper military support after the landing and also the superior military tactics exercised by Castro's highly motivated troops. In fact, President Kennedy denied the invaders adequate military support after the initiation of the invasion because the Soviet Union had previously declared its willingness to aid Cuba in defending itself against the United States by furnishing military aid, including missiles. Nonetheless, after the Bay of Pigs fiasco, Kennedy publicly committed his administration never to tolerate offensive missiles in Cuba [Allison, 1971].

On October 14, 1962, American aerial reconnaissance discovered irrefutable evidence of Soviet offensive missiles being installed at various sites in Cuba. In order to obtain sage advice on a plan of action from as many reliable and relevant sources as possible, President Kennedy created the Executive Committee of the National Security Council. This committee included major cabinet and government agency officers with principal responsibilities for political and military decisions, representatives of major segments of the public, and some special advisors. The Executive Committee formulated a number of possible actions in response to the Soviet threat including taking no aggressive action, executing surgical air strikes against the missile bases in Cuba, and imposing a naval blockade of Cuba by turning back all ships carrying military supplies to Cuba [Able, 1969; Allison, 1971].

Premier Nikita Kruschev, the leader of USSR, had to decide whether or not to withdraw Soviet missiles from Cuba. He could also escalate the conflict through coercive actions such as putting pressure on West Berlin, attacking US naval vessels, bombing Southeastern American targets from Cuba or initiating an ICBM (Intercontinental Ballistic Missile) assault on the US. Because of the wise restraint exercised by the heads of both super powers, the Cuban Missile crisis did not result in nuclear winter. Rather, the US adopted a strategy of blockading military shipments to Cuba, and the USSR withdrew the offensive missiles. To this day, the Americans have kept their promise not to carry out a military invasion of Cuba. In the next two sections the Cuban Missile Crisis is modelled and analyzed for the first time using GMCR II in order to explain many of the key assumptions, concepts and algorithms underlying the graph model for conflict resolution as well as highlight the cleverness of their design for realistically and systematically studying realworld conflict.

3. MODELLING: PUTTING THE CONFLICT INTO PERSPECTIVE

3.1. Multiple Participant – Multiple Objective Decision Making

Within the fields of operational research and systems engineering, formal modelling techniques have been developed for describing a social conflict having two or more participants or decision makers, each of whom can have multiple objectives. More specifically, the graph model for conflict resolution [Fang et al., 1993] constitutes an expansion and reformation of conflict analysis [Fraser and Hipel, 1984], which in turn is an extension of metagame analysis [Howard, 1971]. Other related methods for systematically describing human conflict include drama theory [Howard, 1994], which allows one to consider the role of emotions caused by dilemmas in conflict resolution, and hypergame analysis [Bennett, 1980; Wang et al., 1988], which permits one to take misperceptions into account. The foregoing approaches to strategic decision making situations can be considered as belonging to a branch of game theory that is quite distinct from more traditional methods based on the classical work of von Neumann and Morgenstern [1944]. Hipel et al. [1999] describe the roles of the graph model for conflict resolution and other formal operational research tools for refining and selecting courses of action to solve a given problem within a systems engineering context [Sage, 1982]. As explained in an overview paper by Hipel [2003] and in articles contained within Theme 1.40 on Conflict Resolution in the Encyclopedia of Life Support Systems (EOLSS), a wide range of less formal approaches to conflict resolution have been developed in fields falling outside of systems engineering and operational research, such as psychology, sociology and philosophy. Whatever the case, in Sections 3 and 4, the decision support systems GMCR II [Hipel et al., 1997; Fang et al., 2003a,b] is employed to model and analyze, respectively, the Cuban Missile Crisis outlined in Section 2, using the formal methodology of the graph model for conflict resolution.

3.2. Decision Makers and Options.

The left hand side of Exhibit 2 lists each of the two main decision makers in the Cuban Missile Crisis as well as the options or specific powers under the control of each participant. Notice that the US controls the options of executing a surgical air strike (written as Air Strike in Exhibit 2) as well as implementing a naval blockade of Cuba to prevent further missiles from being shipped to Cuba by the USSR (Blockade). The USSR had the power to withdraw its missiles from Cuba (Withdraw) or escalate the conflict (Escalate). Cuba is not included as a decision maker in this model since it possessed no real power to exercise over the USSR or the US. The decision makers and options shown in Exhibit 2 are the same as those put forward by Fraser and Hipel [1984, Ch.1] who analyzed this dispute using conflict analysis.

The three columns of Y's and N's given in Exhibit 2 represent three possible states, written in option form, that could occur in the Cuban Missile Crisis. A "Y" indicates "yes" the option opposite the Y is selected by the decision maker controlling it, while "N" means "no" the option is not taken. Consider for example, state number 7 which is shown on the far right in Exhibit 2 and represents the equilibrium or resolution to the Cuban controversy. At state 7, the US has followed the strategy of not performing an air strike and selecting the option of blockading Cuba. The USSR had chosen the strategy of withdrawing its missiles and not escalating the conflict. The strategy selections of both decision makers combine to form the overall state numbered as 7.

Reading from left to right, Exhibit 2 traces the evolution of the Cuban Missile Crisis from the status quo state through an intermediate state to the final equilibrium. The arrows indicate the option changes that take place to cause the game to progress from one state to another. Starting at state 1, in which both decision makers have selected none of their options, the US can cause a unilateral movement from state 1 to 3 by implementing a naval blockade. Subsequently, the USSR controls the unilateral change from state 3 to 7 when it decides to withdraw its missiles from Cuba. Equilibrium state 7 is what occurred historically and the way in which the stability of this equilibrium is determined is outlined in Section 4.

Exhibit 2. Decision Makers and Options in the Cuban Missile Crisis as well as the Evolution of the Conflict from the Status Quo through an Intermediate State to the Final Resolution.

Decision Makers And Options	Status Quo State	Intermediate State	Equilibrium State
US			
1. Air strike	N	N	N
2. Blockade	N ⟶	Y	Y
USSR			
3. Withdraw	N	N ⟶	Y
4. Escalate	N	N	N
State Number	1	3	7

Challenge # 1 – Recording Conflicts: The conflict model displayed in Exhibit 2 contains two decision makers, each of whom has two options. In theory, this option form can record any finite number of decision makers each of whom can have any finite number of options. Additionally, a given decision may represent an individual person, a small group of people, a large organization or even a country, which is the case for both decision makers in the Cuban conflict. Surprisingly, the decision technology described in the paper appears to work equally well for any combination of different types of decision makers. This is in sharp contrast to fields such as physics and hydrology where the kinds of models employed can vary radically according to the scale or size of the problem being studied. Moreover, although each option in a conflict model represents a binary choice, since it can be either taken or not, a sensible procedure can be adhered to when one desires to represent a continuum of values or levels for an action. For instance, the escalation of the Cuban Missile Crisis by the USSR could be given as a list of separate options reflecting a number of specific actions that the USSR could adopt. However, for the purpose of the study presented herein, any coercive action by the USSR would represent an escalation of the dispute and this can be most parsimoniously given as one overall option.

3.3. Feasible States

The decision support system GMCR II allows a user to conveniently enter into the computer the decision makers and options, which are listed in the left column in Exhibit 2 for the case of the Cuban Missile Crisis. Because an option can either be selected or rejected, a conflict having k options contains a total of 2^k mathematically possible states. Hence, a dispute such as the Cuban conflict possess 2^4 or 16 possible states while a conflict having a total of 20 options across all of the decision makers has more than one million possible states! Clearly, one is heading directly into a "combinatorial brick wall" which, fortunately, can be cleverly scaled.

Challenge # 2 – Handling a Large Number of States: No matter how many states are included in a game model, the reader should keep in mind that they are all automatically generated by GMCR II. Because GMCR II possesses an effective design for its data structure and is programmed using C^{++}, it is purposely constructed for taking care of small, medium and large conflicts. More particularly, a 32-bit DOUBLEWORD is utilized to represent the specific option selection defining a state wherein each digit or bit equals 1 or 0 to indicate whether or not the option it represents is taken or not. Since there are 32 bits, this design can accommodate up to 32 options, which is more than abundant for realworld applications. Moreover, one can greatly reduce the number of feasible states to be considered by eliminating infeasible states which could not possibly occur and combining states which are essentially the same. Efficient algorithms for accomplishing the foregoing are encoded within the user interface program for GMCR II [Hipel et al., 1997; Fang et al., 2003a,b].

Exhibit 3 shows GMCR II's dialog box for specifying infeasible states using one or more of four specific procedures which are described in detail elsewhere [Hipel et al., 1997; Fang et al., 2003a,b]. For the case of the Cuban conflict, the user has indicated in Exhibit 3 that he or she would like to remove infeasible states which are mutually exclusive. Because it is not realistic for the USSR to withdraw its missiles and escalate the conflict at the same time, the third and fourth options are checked as being mutually exclusive in the dialog box displayed in Exhibit 4. Finally, Exhibit 5 shows the twelve feasible states that remain in the Cuban conflict after GMCR II removes the four infeasible ones. In practice, it has been found that a fairly high percentage of infeasible states are eliminated, especially for larger games. For instance, after removing infeasible states from a twenty-option model describing an international trading conflict, about 185,000 feasible states were left from a possible million states.

3.4. Allowable State Transitions

For any feasible state, a particular decision maker may be able to unilaterally cause a transition from one state to another state by changing his or her option selection. For example, in Exhibit 2, the US controls the unilateral move from state 1 to 3 while the USSR causes the state transition from state 3 to 7. GMCR II automatically calculates all possible state transitions, if present, from each state for each decision maker.

Exhibit 3. Selection of Procedure(s) for Specifying Infeasible States.

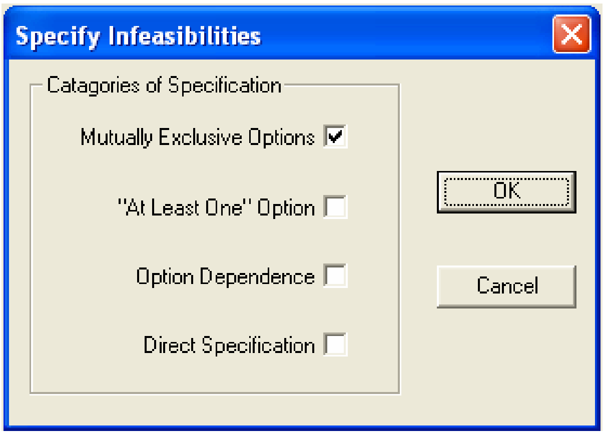


Exhibit 4. Mutually Exclusive Options in the Cuban Missile Crisis.

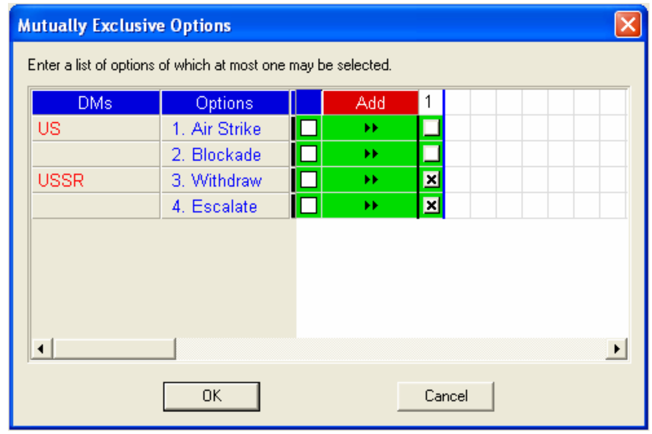
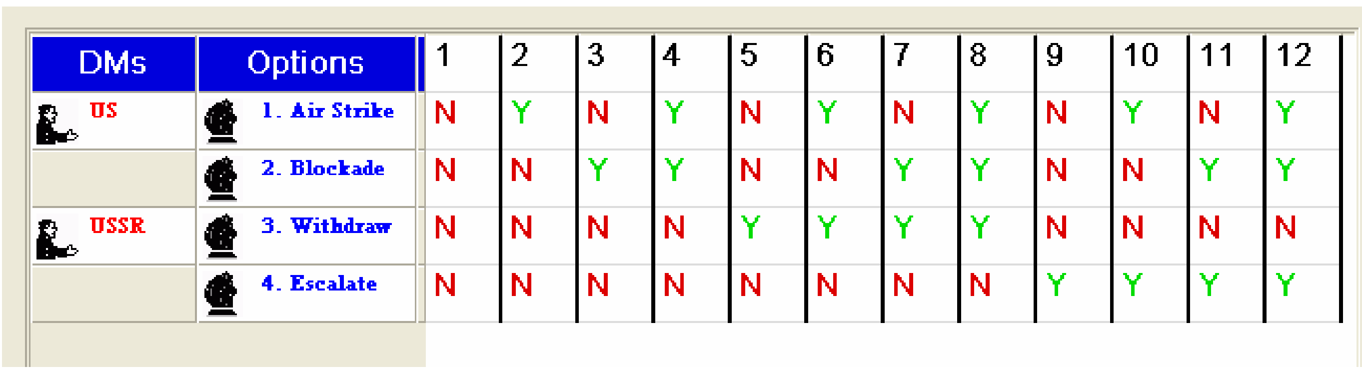


Exhibit 5. Feasible States in the Model of the Cuban Missile Crisis.



DMs	Options	1	2	3	4	5	6	7	8	9	10	11	12
US	1. Air Strike	N	Y	N	Y	N	Y	N	Y	N	Y	N	Y
	2. Blockade	N	N	Y	Y	N	N	Y	Y	N	N	Y	Y
USSR	3. Withdraw	N	N	N	N	Y	Y	Y	Y	N	N	N	N
	4. Escalate	N	N	N	N	N	N	N	N	Y	Y	Y	Y

Challenge # 3 – Keeping Track of Irreversible Moves: As can be seen in Exhibit 5, the US unilaterally controls the state transition from state 1 to 2 by executing a surgical air strike of the missile bases in Cuba. However, after the missile sites are bombed the damage is inflicted and the Americans cannot move back to state 1 from state 2. Hence, the transition from state 1 to state 2 is irreversible and one would like to have a model that can take this into account. Theoretically, the graph model for conflict resolution has a finite directed graph for each decision maker in which the vertices represent the feasible states and the state transitions are the arcs on the graph connecting the vertices. Allowable state transitions in both directions between two states are indicated by two arrowheads pointing in opposite directions whereas an irreversible move is marked using a single arrowhead. From an implementation viewpoint, GMCR II uses what is called a reachable list to keep track of the set of allowable state transitions for a given feasible state and decision maker. Unless, it is not specified by the user, the program assumes that feasible unilateral movement can take place in both directions between two states for a given decision maker. Exhibit 6 explains how a user can specify irreversible moves brought about by the US executing an air strike.

3.5. Relative Preferences

Challenge # 4 – Preference Elicitation: Usually the most difficult hurdle to overcome in calibrating a decision model is to obtain accurate preference information. A noteworthy advantage of GMCR II is that it requires only relative preference information among states for each decision maker. Additionally, a flexible set of tools is available for conveniently entering this preference information into the computerized system. Therefore, for a given decision maker, the analyst needs to specify whether one state is more preferred than another, less preferred, or equally preferred and there is no need to estimate the "magnitude" of this preference. Hence, the problem of obtaining cardinal preference information, such as utility values, is avoided. Stated differently, the user of GMCRII has to somehow enter a ranking of states from most to least preferred for each decision maker, where some states may be equally preferred. The possibility of preference ties permits stability analyses even when the analyst lacks some preference information. In practice, this means that one can start with a "quick and dirty" analysis and subsequently refine preferences as more information becomes available. Although GMCR II assumes that the preferences for each decision maker are ordinal, and thus transitive, theoretically, the graph model for conflict resolution can handle a broader variety of preference types including intransitivity [Fang et al., 1993, Ch. 8]. Finally, the option prioritizing approach to obtaining relative preference information for each decision maker explained in this section accurately reflects the manner in which a person may contemplate his or her values or preferences in a specific conflict situation.

Exhibit 6. Specifying Irreversible Moves in the Cuban Missile Crisis.

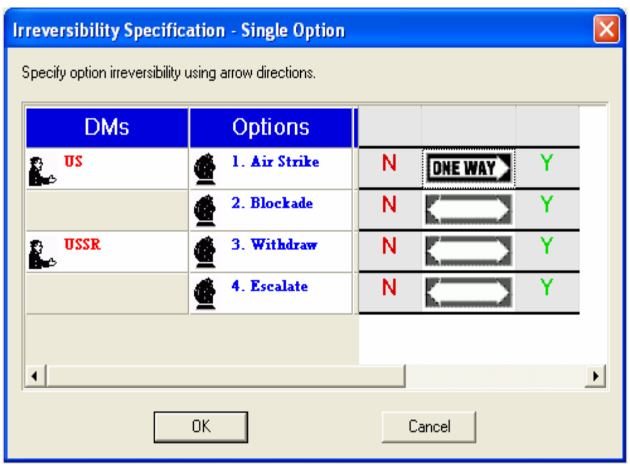
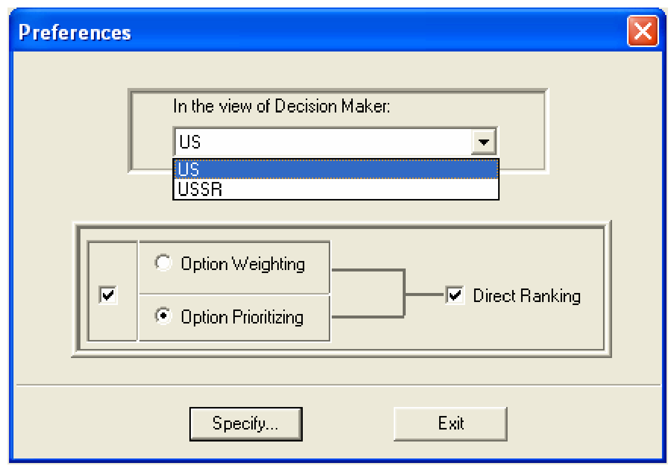


Exhibit 7. Obtaining Relative Preference Information for the US in the Cuban Missile Crisis.



To avoid pairwise comparisons of states to obtain relative preferences in moderate and large-size conflicts, GMCR II has two approaches to procuring at least an approximate ranking of states. Subsequently, GMCR II enables the user to fine tune the initial state ranking, if needed. Exhibit 7 summarizes the main steps to be followed as GMCR II elicits relative preference information from a particular decision maker. Because the US is highlighted, preferences will be entered for this decision maker. One can obtain a ranking of states using preference information expressed in terms of the options using either the Option Weighting or Option Prioritizing approach. Either of these procedures is ideal for entering preferences in larger models but can in fact be employed with any size of dispute. The Direct Ranking feature can be used to fine tune, if required, a ranking initially obtained using Option Weighting or Option Prioritizing. Moreover, if desired, one can go directly to Direct Ranking and arrange the states in order on the screen. In Exhibit 7, the current status of the check box and radio boxes on the left indicates that the user has decided to use Option Prioritizing to first rank the states using preference information about options. The fact that the right check box is turned on means that, if required, the user may fine tune the initial ranking using Direct Ranking as the next step.

When employing Option Weighting, one simply assigns a numerical weight to each option for a particular decision maker. The greater the weight, the more preferred the option. Negative weights indicate options that the decision maker prefers not be selected. For a specified state, the weights are summed across the options and subsequently GMCR II ranks the states from most to least preferred where ties are allowed. One should bear in mind that the magnitude of the weights is not meaningful, and is used only to indicate relative preferences.

The Option Prioritizing approach in GMCR I constitutes a generalization of the "preference tree" method originally proposed by Fraser and Hipel [1988] and later expanded upon by Fang et al. [2003a]. Exhibit 8 demonstrates how Option Prioritizing is used in GMCR I while Exhibit 9 shows how GMCR II ranks the states from most preferred on the left to least preferred on the right using only the preference information listed on the right in Exhibit 8. Essentially, this approach ranks states according to the truth or falsity of logical statements about option selections. In Exhibit 8, the importance of a preference statement is indicated by its position, with more important statements higher in the list. The numbers in Exhibit 8 refer to specific options which are numbered on the left. A negative sign to the left of an option indicates that the option is not taken. The 3 entered at the top of the list of preference statements on the right side of Exhibit 8 means that the US most prefers that the USSR withdraws its missiles from Cuba by selecting option 3. Notice that the four states containing a Y opposite option 3 are listed on the far left in Exhibit 9 since they are more preferred than the eight states having an N beside option 3. Next, the Americans prefer that option 4 not be taken as indicated by the -4 typed below the 3 on the right in Exhibit 8. This preference statement causes states having an N opposite option 4 to be placed to the left of those with a Y beside option 4, while still maintaining the hierarchical importance of the preference of option 3 given above -4 in Exhibit 8. The third level preference statement written as -1 if 3 means that the US prefers that option 1 be rejected (-1) if option 3 is taken. This explains, for example, why states 5 and 7 are preferred to states 6 and 8 in Exhibit 9. In fact, the preference statements on the right in Exhibit 8 are based upon first order logic and each preference statement takes on a truth value of being either true or false. Even though the preference statements are written in terms of option numbers, they do in reality reflect the way one may verbally express preferences in an actual conflict situation. Consider, for example, the seventh preference statement from the top in Exhibit 8 which is written as 1|2 if -3 and -4. This simply means that the US prefers carrying out an air strike (1) or blockade (2) if the USSR does not withdraw its missiles (-3) and does not escalate (-4). By carefully examining the hierarchical list of preference statements in Exhibit 8, one can appreciate how the algorithm in GMCR II lexicographically ranks the states as shown in Exhibit 9. No additional fine tuning is required to obtain this ordering of states which contains no sets of equally preferred states and hence is strictly ordinal.

Exhibit 8. Option Prioritizing for the US in the Cuban Missile Crisis.

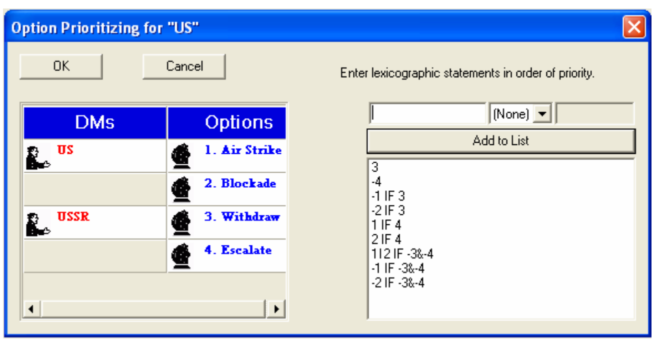
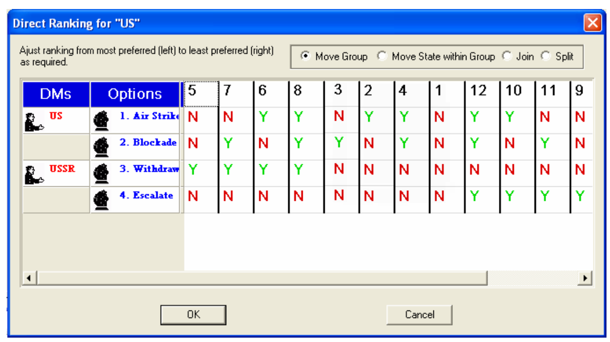


Exhibit 9. Ranking of States using Option Prioritizing for the US in the Cuban Missile Crisis.



The hierarchical list of preference statements written horizontally in text for the USSR is -4, 1 if 4, 2 if 4, -1 if -4, -2 if -4, 3 iff (if and only if) 1|2. The option prioritizing algorithm in GMCRII then ranks the states from most to least preferred using the state numbers as (1, 5, 7, 3, 6, 2, 8, 4, 12, 10, 11, 9).

The author was interested to discover which type of preference elicitation technique, option weighting or option prioritizing, is more desirable to use in practice. As part of the course requirements for SYDE 533, Conflict Analysis, taught by the author in the Department of Systems Design Engineering at the University of Waterloo from September to December each year, 79 groups of fourth-year engineering students, who took the course for credit in 1997, 1998, 2000 and 2001, used GMCR II to model and analyze realworld conflicts chosen by the groups and presented their findings in a final report. Additionally, the 79 groups were requested to use both option weighting and option prioritizing in their conflict studies and to fill in a preference questionnaire, the results of which are summarized in Exhibit 10. As can be seen, overall, 53 of 79 groups prefer option prioritizing over option weighting. When the two preference elicitation methods are compared according to the other criteria given in the left column, option prioritizing is more desirable according to all but one of the criteria. According to the survey, even though option weighting is the most convenient to use, it is not as realistic, informative and accurate for ranking states for a given decision maker. Whatever the case, both methods are relatively easy to utilize in practice before any further sorting using direct ranking, and they are the only two reasonable methods that are currently available for state ordering when dealing with medium-sized and large conflicts.

4. ANALYSIS AND RESULTS: DECIDING WHAT TO DO

4.1. Stability Analysis

Challenge # 5 – Realistically Describing Human Behavior in Conflict Situations: Because people think and react to circumstances in rather nonquantitative and uniquely human ways, does it make sense to try to systematically describe the manner in which people make decisions through some type of formal mathematical modelling? The answer to this challenge is yes, as long as it is done nonquantitatively. In particular, within the paradigm of the graph model for conflict resolution, solution concepts, which mathematically define different ways in which humans may behave under conflict, are precisely defined using set theory, logic and graphs – the mathematics of relationships. As noted earlier, possible unilateral movements that a decision maker can make from states in one step are encapsulated theoretically within a directed graph or implemented practically using reachable lists within GMCR II. Accordingly, the graph model methodology is rigorously mathematical and axiomatic, yet completely nonquantitative. The most that is assumed about the preference structure for a decision maker is ordinality and cardinal preferences are not required. Hence, there is no cardinal quantification whatsoever within this unique decision technology. Moreover, the graph model offers decision makers and other interested parties valuable insights into possible compromise resolutions to a given dispute, how a given decision maker may wish to respond in an optimal way within the social constraints of the conflict, when it is advantageous to cooperate with others, and how the conflict could dynamically evolve to an eventual resolution.

Exhibit 10. Findings of the Preference Questionnaire completed by 79 Groups.

Criteria	Option Weighting	Option Prioritizing
Most preferred method	26	53
Most realistic	22	57
Most informative	35	44
Most convenient to use	42	37
Best for obtaining a preliminary ranking before using direct ranking	37	42

Within Section 3, a conflict model was developed for the Cuban Missile Crisis in terms of decision makers and options (Exhibit 2), feasible states (Exhibits 3 to 5), allowable state transitions (Exhibit 6), and relative preferences (Exhibit 7 to 9 for the US and within the text of Section 3.5 for the USSR). This calibrated conflict model developed within the input interface component of GMCR II is now entered into the main engine of GMCR II where an exhaustive stability analysis is executed. In general, a particular state is stable for a decision maker if it is not advantageous for that decision maker to move away from the state unilaterally by changing the selection of options under his or her control. Additionally, a state is automatically stable for any decision maker who cannot move away from it. However, if a decision maker 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 is such a description and is therefore a sociological model of behavior in a strategic conflict. When a given state is stable for all decision makers according to a given solution concept, it is deemed to be an equilibrium or compromise resolution since no decision maker has an incentive to move away from it with respect to that solution concept.

Exhibit 11 lists and characterizes solution concepts that are encoded within the engine of GMCR II for use with conflicts involving two or more decision makers. The first column gives the names of the solution concepts and associated acronyms while the second column provides a description as to how each solution concept works (Kindly refer to Fang et al. [1993] for original references for these solution concepts.). The last four columns furnish characterizations of the solution concepts in a qualitative sense, according to the four criteria of foresight, disimprovements, knowledge of preferences and strategic risk. Foresight constitutes a reflection of the number of moves and countermoves that a decision maker can envision when deciding upon the stability of a state. Disimprovement refers to the tendency of a decision maker to put itself in a less preferred situation to sanction unilateral improvements by a competitor. The characteristic called knowledge of preferences means the preference information needed to execute a stability analysis. Finally, strategic risk refers to the attitude of a decision maker to risk, which can range from ignoring risk under Nash tability to embracing risk under nomyopic behavior.

In their book, Fang et al. [1993] define (Chapter 3) and mathematically compare (Chapter 5) the solution concepts listed in Exhibit 11. Additionally, they demonstrate how the graph model and an associated solution concept can be equivalently expressed using an extensive game, which is much more complicated and hence not as well suited for practical applications (Chapter 4). Hence, they illustrate the exact theoretical connections between the graph model for conflict resolution and classical game theory.

After a model has been established, a GMCR II analysis furnishes an assessment of the stability of every state, from the point of view of every decision maker, under all of the stability definitions listed in Exhibit 11. The three states that are stable according to sequential stability and limited move stability for various horizons h, are states 5, 6 and 7. This means that if the conflict were to arrive at one of these states, it would stay there since it is an equilibrium. However, as shown in Exhibit 2, it is state 7 which can be reached from the status quo state 1 via state 3. Specifically, the US brings about a unilateral improvement from state 1 to 3 by imposing a naval blockade of Cuba. The USSR can then unilaterally take advantage of its unilateral improvement by withdrawing its missiles and causing the conflict to move to state 7, the resolution that took place historically.

Exhibit 11. Solution Concepts and Human Behavior (Based upon Table 6 in Hipel et al. [1997])

Solution Concepts	Stability Description	Foresight	Disimprovement	Knowledge of Preferences	Strategic Risk
Nash stability (**R**)	Decision maker cannot unilaterally move to a more preferred state.	Low	Never	Own	Ignores risk
General Metarational (**GMR**)	All focal decision maker's unilateral improvements are sanctioned by subsequent unilateral moves by others.	Medium	By opponents	Own	Avoids risk; conservative
Symmetric Metarational (**SMR**)	All focal decision maker's unilateral improvements are still sanctioned even after a possible response by the original decision maker.	Medium	By opponents	Own	
Sequential Stability (**SEQ**)	All of the focal decision maker's unilateral improvements are sanctioned by subsequent unilateral improvements by others.	Medium	Never	All	Takes some risks; satisfies
Limited-move Stability (**L_h**)	All decision makers are assumed to act rationally within a fixed number of state transitions (h).	Variable	Strategic	All	Accepts Risk; strategizes
Non-myopic Stability (**NM**)	Limiting case of limited-move stability as the maximum number of state transitions increases to infinity.	High	Strategic	All	

State 5 did not occur as the historical equilibrium because in order for it to be reached from the status quo state 1, the USSR would have to invoke a unilateral disimprovement from state 1 by withdrawing its missiles on its own without any coercive action by the US. In fact, when the Americans imposed a naval blockade, the USSR decided to withdraw its missiles and thereby appear as a peacemaker to the rest of the world. It is interesting to point out that state 6, where the US performs surgical air strikes and the Russians remove their missiles, is an equilibrium because dropping bombs on the Soviet missile bases is considered to be irreversible in Exhibit 6. When this irreversibility restriction is dropped, state 6 does not remain as an equilibrium.

The results from an analysis can be employed for explaining why a state is stable or unstable for a given decision maker according to any of the solution concepts in Exhibit 11. Consider, for example, why the equilibrium state 7 is stable according to the solution concept of sequential stability for the US in the Cuban Missile Crisis. As can be seen in Exhibit 9, the US can unilaterally improve from state 7 to 5 by removing the naval blockade (Notice in Exhibit 9 that state 5 is more preferred by the US to state 7 and the Russian strategy of withdrawing its missiles is the same in both states. Hence, state 5 is a unilateral improvement (UI) for the US from state 7.). However, the USSR has its own UI from state 5 to state 1, when it decides not to withdraw its missiles. Because state 1 is less preferred to state 7 by the US (see Exhibit 9), the potential UI from 7 to 5 for the US is credibly blocked by the USSR. As can be seen by examining Exhibit 9, the only UI that the US has from state 7 is state 5. Therefore, all of the UI's from state 7 are credibly sanctioned and state 7 is stable according to sequential stability (SEQ) for the US. Exhibit 12 portrays the aforesaid reasoning for the stability of state 7 for the US.

From state 7, the USSR has no UI's that it can invoke. Hence, state 7 is stable according to rationality (R) for the USSR. Because state 7 is stable for both decision makers, it forms a possible compromise solution or equilibrium in the Cuban Missile Crisis.

As noted earlier, each of the solution concepts in Exhibit 11 is precisely defined mathematically for conflicts having two or more decision makers. For instance, the mathematical definition for sequential stability for a conflict having two decision makers i and j is as follow [Fraser and Hipel, 1984; Fang et al., 1993, Ch. 3]:

Definition of Sequential Stability: For a decision maker $i \in N$, a state $k \in U$ is sequentially stable (SEQ) for decision maker i iff for every $k_1 \in S_i^+(k)$ there exists $k_2 \in S_j^+(k_1)$ with $k_2 \leq_i k$, where N is the set of decision makers, U is the set of states, $S_i^+(k)$ is the set of UIs for decision maker i if from state k, $S_j^+(k_1)$ is the set of UIs for decision maker j from state k_1, and $k_2 \leq_i k$ means that state k_2 is less preferred or equally preferred to state k by decision maker i. A rational state is actually a subset of the sequential stability definition for the special situation in which the set $S_i^+(k)$ is empty. As is the case for the theoretical definitions of all solution concepts in Exhibit 11, special algorithms are programmed within the engine of GMCR II to calculate sequential stability for a particular state and given decision maker. For the case of state 7 in Exhibit 12, one can see that 7 satisfies the definition of sequential stability when the following substitutions are made: i = US, j = USSR, N = {US, USSR}, k = 7, U is the set of twelve states listed in Exhibits 5 and 9, $k_1 = 5$, $S_i^+(7) = \{5\}$, $k_2 = 1$, $S_j^+(5) = \{1\}$ and $1 <_i 7$.

Exhibit 12. Stability of State 7 for the US According to the Sequential Stability Solution Concept.

	More preferred by US	Particular State	Less preferred by US
US			
1. Air strike	N	N	N
2. Blockade	N	Y	N
USSR			
3. Withdraw	Y	Y	N
4. Escalate	N	N	N
State Number	5	7	1

UI for US (from 7 to 5)

UI for USSR (from 5 to 1)

Exhibit 13. Preferences used in the Hypergame Analysis.

Preferences Envisioned by the US
US Preferences
5 7 6 8 3 2 4 1 12 10 11 9
USSR Preferences
1 5 7 3 6 2 8 4 12 10 11 9
Preferences Envisioned by the USSR
US Preferences
5 1 7 3 6 2 8 4 12 10 11 9
USSR Preferences
1 5 7 3 6 2 8 4 12 10 11 9

4.2. Hypergame Analysis: Consideration of Misperceptions

A hypergame is a conflict in which one or more of the decision makers has a misunderstanding about one or more aspects of the dispute [Bennett, 1980; Fraser and Hipel, 1984; Wang et al., 1988]. Because the US had performed so poorly at the Bay of Pigs invasion, as well as other reasons, Premier Kruschev expected a weak response from the US to the placement of Soviet missiles in Cuba [Able, 1969; Allison, 1971]. One possible manifestation of Kruschev's faulty interpretation of the American preferences is the ranking of states for the US in the lower part of Exhibit 13. Notice that the top part of Exhibit 13 displays the correct preferences for both the US and USSR, while the lower portion shows how the USSR incorrectly interprets American intentions but, of course, correctly understands its own desires. For example, Kruschev incorrectly believes that the status quo state 1 is more preferred by the US over states containing aggressive action by the US.

In Section 4.1, GMCR II was used to analyze the conflict model shown in the upper part of Exhibit 13 and predicted state 7 as the most likely result, with the other equilibria being states 5 and 6. When the conflict model shown in the lower half of Exhibit 13 is entered into the engine of GMCR II, the only predicted equilibrium according to SEQ and L_h for various horizons h is state 1. In other words, Kruschev incorrectly thinks that the status quo state is going to persist, and, hence he will be able to keep his missiles in Cuba with no American response. Accordingly, when the US imposes a naval blockade, Kruschev is caught by surprise and his new knowledge of the situation causes the hypergame to disappear and results in the game shown in the top part of Exhibit 13. Premier Kruschev then responds by withdrawing Soviet missiles from Cuba.

4.3. Sensitivity Analyses

Challenge # 6 – The Practical Effectiveness of GMCR II: A question that often arises with almost any type of decision tool is whether or not it will perform well in practical situations and thereby be utilized by realworld decision makers for actually providing decision support to help solve pressing problems. This author and his colleagues believe that this is the case for GMCR II, for which the output interface is currently being completed. Of practical import is the fact that GMCR II assists an interested party in better understanding the strategic consequences of a specific model of a given conflict. Although no one is ever completely certain of what will happen in the future, at least the potential results of a range of possible strategy choices can be much better envisioned using GMCR II. Recall that President Kennedy, for example, obtained crucial advice on various ways to respond to the Russian placement of missiles in Cuba, from people with different backgrounds and knowledge who were members of the Executive Committee of the National Security Council. In a sense, President Kennedy was carrying out his own sensitivity analyses of what could potentially happen if he followed the advice of either his "hawks" or "doves", or adopted some policy that fell between the two extremes. Although GMCR II and many other formal models were not a available in 1962, there is little doubt that President Kennedy was very rational and sensible in his thinking process. Additionally, as explained within Section 5 on future Challenges, GMCR II can be significantly expanded to handle a rich range of new theoretical developments in areas such as preference elicitation, formalizing emotional thinking, and coalition analysis. As emphasized in Section 1 and Exhibit 1, GMCR II can form a valuable tool for use in strategic analyses in conjunction with other societal and physical decision support systems for reflecting the key characteristics of a current systems engineering problem being formally investigated.

Determining changes in equilibrium results due to different preference structures for one or more decision makers, constitutes one of the most common kinds of sensitivity analyses. For example, when one is not completely certain of the preferences of one of the decision makers, one can analyze a reasonable range of preferences to ascertain how the equilibria are affected. If, for instance, the predicted equilibria do not change over a range of preference structures, then the equilibria are robust with regards to those preferences.

Especially when using GMCR II to help decide what to do in a current dispute, one would usually like to carry out sensitivity analyses by considering the strategic implications of a sensible range of different, but related models, of the conflict under study. Where misunderstandings may be present or one party wishes to deliberately misinform another, the hypergame analysis of Section 4.2 could be used in conjunction with GMCR II.

Currently, one can determine the best situation each decision maker can hope to achieve on his or her own using the output from GMCR II. This system is now being expanded in its output interface component to allow coalitions and cooperation among decision makers [Kilgour et al., 2001] to be considered to ascertain if a decision maker can do better by joining forces with others. Whatever sensitivity analysis is thought to be worthwhile to pursue, GMCR II allows its strategic results to be immediately analyzed and interpreted.

5. FUTURE CHALLENGES

This author firmly believes that the demand for having a range of useful conflict resolution methodologies for addressing a spectrum of realworld conflict situations is going to continue to increase in the future. Although the Cold War has come to an end and the accompanying threat of a global nuclear war has thereby greatly decreased, a number of new types of conflicts are arising while others are becoming more serious. For instance, the adoption of democracy and market-oriented economies by most of the nations of Eastern Europe since the fall of communism has meant that political differences now abound among political parties within a given country, and there is fierce business competition within and among countries. In the 1990's and start of the 21st century, nationalism and cultural differences have created nasty civil wars to erupt in countries such as the former Republic of Yugoslavia and Russia. The ongoing devastation of the earth's natural environment by the economic advancement of civilization and huge population increases, have caused serious environmental problems such as global warming or climatic change, and pollution of water, land and air throughout the world. This in turn has caused serious conflicts to arise between proponents of development and environmentalists as they strive to reach a balance between economic progress and environmental stewardship, which is popularly referred to as sustainable development. At the international level, negotiations have taken place in an effort to reach agreement over important issues such as reductions in the emission of greenhouse gases within the Kyoto Protocol, and having free trade in services. It is interesting to note that most of the scientific and engineering solutions required for cleaning up pollution in the environment are well known but the political and economic means for realistically implementing them are not. The foregoing and a host of other examples of differences in opinion dictate the need for developing a rich variety of decision tools for use in conflict resolution and there is little doubt that concepts in computational and systems engineering will play a key role in these developments.

One example of a major area in conflict resolution in which more formal models are greatly needed is the situation where negotiators attempt to benefit everyone taking part in the negotiations. Fisher et al. [1991], Raiffa [1982, 2002] and Radford [1988] suggest general procedures for encouraging decision makers to work together in order to come up with creative solutions that are more preferred by all parties – the so-called win/win solutions. Within the graph model paradigm, the author and his colleagues are designing a new model structuring component that would allow the decision technology to be more easily used for brain-storming sessions when groups cooperate to devise imaginative alternative solutions [Song et al., 2001]. In a brain-storming session taking place at higher levels of decision making or near the start of a dispute, decision makers tend to think about final desirable outcomes rather than specific option choices to arrive at these outcomes. Hence, nodes standing for possible states could be drawn to suggest paths represented as arcs for reaching various states, for each of the decision makers. Even the relative preferences for each decision maker can be entered using a directed graph. Because the graph model for conflict resolution assumes that states are the basic units among which strategic interactions occur, the current engine of GMCR II could be used to produce the stability results for the graphical model input.

As noted in Section 3.5 under Challenge #4, a crucial step in calibrating a conflict model is obtaining reliable relative preference information for each decision maker involved in a dispute. Research is well underway for expanding the scope of the graph model for handling a richer variety of relative preference information that arises in practice. For example, the definitions of the top four solution concepts listed in Exhibit 11 have been revised for taking into account strength of preference when a decision maker greatly prefers or greatly dislikes one state with respect to another [Harmonda et al., 2004]. For instance, the USA and other counties may greatly not prefer a situation or state in which North Korea develops nuclear weapons relative to a state in which it does not. Hence, the threat of North Korea building nuclear weapon can form a strong sanction against threatening actions by other countries. In certain conflicts, some of the relative preferences between states by one or more decision makers may be unknown and this knowledge can be incorporated into the definitions of the first four solution concepts given in Exhibit 11 for employment in stability calculations [Li et al., 2004]. Ben-Haim and Hipel [2002] present an information gap approach for systematically addressing uncertainty in the preferences of a decision maker which can be used, for instance, for determining the robustness of equilibria under rigorous sensitivity analyses executed within a conflict study.

Research is well underway for ascertaining how a describable equilibrium or other state can be reached from a status quo state using a variety of algorithms collectively referred to as states quo analysis [Li et al., 2004]. Moreover, the roles that both positive and negative emotions can play in a graph model study are being formally incorporated into the graph model methodology in a range of meaningful ways [Obeidi et al., 2003]. Existing and new advances in the graph model approach can be used to determine the best that a given decision can hope to achieve within the social and strategic constraints of a conflict. A subsequent question to address is whether or not a decision maker can do even better by cooperating with others in a process called coalition analysis. One preliminary, yet significant, approach to research in coalition analysis is presented by Kilgour et al. [2001] for employment within the graph model paradigm. Finally, it is planned to develop a new generation of the decision support system GMCR II that possesses the foregoing and other capabilities of the graph model methodology within a truly systems engineering approach to conflict resolution.

Acknowledgements

An earlier version of this paper was originally presented by the author as a Plenary Lecture at the Symposium on Signal Processing and Cybernetics, IMACS Multiconference on Computational Engineering in Systems Applications (CESA), sponsored by IMACS and the IEEE Systems, Man, and Cybernetics Society, and held at Nabeal-Hammamet, Tunisia, from April 1 to 4, 1998. The author is most grateful to the Conference Organizers for inviting him to present a Plenary Lecture at CESA'98 in Tunisia. The development of the theory and practice of the graph model for conflict resolution is a result of joint research that the author carried out with his colleagues (see for example, Fang et al., [1993], Fang et al. [2003a,b], Hipel et al. [1997], and Kilgour et al. [2001]). The copyright for the decision support system GMCR II, which was used for executing the modelling and analysis of the Cuban Missile Crisis, is held by L. Fang, D. Marc Kilgour, X. Peng and the author. Mr. Y. Chen kindly assisted in preparing the final version of this paper.

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