Chapter Ten

USING EXPLORATORY MODELING

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This chapter examines a way to use combat modeling that both capitalizes on the strengths of combat models and helps analysts and decisionmakers gain new insights into complex problems.

The chapter has three sections. The first of these describes the evolving defense environment, to show the need for tools that allow analysis of situations dominated by uncertainty. It also briefly discusses combat models in general and the Joint Integrated Contingency Model (JICM) in particular, covering some features of the JICM that make it especially suitable for exploratory modeling. Finally, the section compares conventional sensitivity analysis to exploratory modeling.

The second section describes how exploratory modeling is done, discussing its experimental design and its measures of outcome. It also presents a comprehensive example of applied exploratory modeling, identifying the problem and illustrating some conclusions. The third section then briefly describes exploratory modeling's key advantages.

THE NEED FOR EXPLORATORY MODELING

This book underscores the fact that the national security environment has changed dramatically and continues to change. During the Cold War, the role of U.S. military forces was to prepare for a major war in Central Europe. Other requirements—preparing to fight in Korea or in smaller-scale conflicts—were considered "lesser included cases" of the requirement for Central Europe. With the fall of the Berlin wall, the role of the U.S. military is now to prepare for a variety of contingencies, including terrorist threats. Although the nature of the future defense environment is unclear, long-term deployments to rescue "failed states" such as Afghanistan seem more likely, while having to commit forces to a major theater war (MTW) appears less so. These smaller but more likely operations are difficult to analyze. They are not amenable to many analytic tools and are dominated by uncertainties, ranging from the nature of the conflict, to the location, to the possible reactions to U.S. actions taken in response to evolving conditions.

At the same time, despite the stunning immediate aftermath of the September 11 attacks, many of these contingencies or deployments, in and of themselves, will invoke only limited national interests. The use of overwhelming force is one way to limit casualties, but sending large force deployments to problem areas stresses the rotation base of the services. The culmination of these stresses is a push for new ways of pursuing national security interests, which, in turn, creates a demand to analyze new alternatives.

Exploratory analysis is a tool to aid decisionmaking in such uncertain environments. It applies combat modeling to analytic problems in ways that have not been widely used. In particular, it uses the enormous computation capabilities of modern computers to intensively explore alternative outcomes by systematically varying assumptions. Paul Davis's Chapter Nine describes the technique in great detail. This chapter provides concrete illustrations of how this powerful technique can be used.

Given both the limitations and utility of models, it remains true that model-aided analysis says more about the analyst than about the model. It is the analyst who must judge how to represent the myriad details of the situation under study. In a nutshell, all combat models are wrong. But some, in conjunction with intelligent analysts, can be useful.

The Joint Integrated Contingency Model

The RAND-developed JICM is one such useful model. It employs modular functional submodels (some of which are listed in Figure 10.1) to manipulate the objects represented within the overall model.

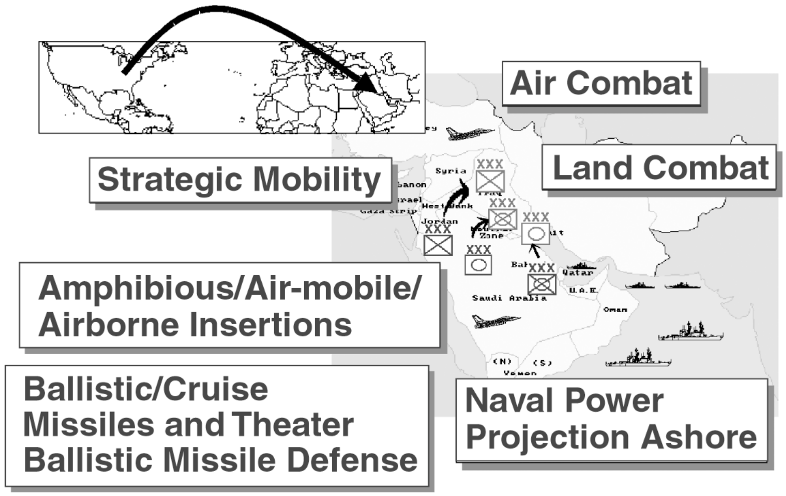


Figure 10.1—JICM Functional Submodels

In JICM, one functional submodel is the simulation's strategic mobility module, which allows the analyst to set up simulation experiments that explicitly include enemy actions intended to degrade U.S. mobility. The degradation in mobility causes adjustments to the arrival of U.S. forces, which, in turn, can affect downstream theater-level outcomes.

Most theater combat models use a scenario input file that is a linear presentation of the events to be simulated.[1] By contrast, JICM uses analytic war plans that explicitly implement the major operational-level decisions of the campaign and allow the campaign to develop along alternative paths in accordance with how the simulated situation evolves. Within JICM, the war plans can query the state of the simulation and then alter actions taken by entities in the simulation

[1]The linear presentation generally describes the major operational events in terms of the fixed time when they are to occur in the simulation. Such events include the arrival of forces, and the timing of offensive and counteroffensive actions.

based on the results of the queries. Three examples of this kind of query are

1. If ?control[KuwaitCity]==Iraq then "do not use POMCUS"
2. If ?location[1-CAV/1-BDE]==KuwaitCity then "implement delay"
3. If (?tooth[EUSA] > 600 && ?tail[EUSA] > 800) then "begin CO"

Query 1 checks to see if Iraq has gained control of (the JICM place) Kuwait City. If so, the analytic war plans select a set of orders that does not involve attempting to use prepositioned combat equipment there. Query 2 verifies that a specific early-arriving force has arrived at Kuwait City. If so, the analytic war plans select a set of orders that implements actions to delay the advance of enemy forces in order to provide time for additional forces to arrive. Query 3 verifies that sufficient combat force and support ("tooth" and "tail") have arrived to begin the counteroffensive.

In JICM analysis, a single analytic war plan can include enough logic to react to the major operational turning points of a conflict. There is no need to create individual linear-order sequences for each alternative case to be examined.

Sensitivity Analysis and Exploratory Modeling

As is true for most models, the use of combat models typically involves some form of sensitivity analysis. In basic form, sensitivity analysis consists of three steps:

1. Establish a base case and obtain results
2. Define an alternative case by changing one or more input variables and obtain new outcomes
3. Compare the base case and alternative case, repeating steps 2 and 3 as required.

In contrast to sensitivity analysis, exploratory analysis is a more intensive process in which a range of values for a set of input variables is defined. Exploratory analysis then executes the simulation for every combination of values for all variables. Full enumeration of all possible cases can quickly mushroom to a very large number of runs.

Varying the numbers of variables and the number of values assigned to those variables produces numbers of runs for conventional sensitivity and exploratory modeling as follows:

- Conventional sensitivity: To explore sensitivity to n variables with m values each, the experiment size is 2 raised to the n^{th} power and the number of runs is thus, e.g.,

  32 with n = 5, m = 2

  1,024 with n = 10, m = 3

  1,048,576 with n = 20, m = 4.

- Exploratory modeling: To explore an experiment with n variables with m values each, the experiment size is m^n and the number of runs is thus, e.g.,

  32 with n = 5, m = 2

  59,049 with n = 10, m = 3

  greater than a trillion with n = 20, m = 4.

Figure 10.2 shows the hours or computers needed for simulation runs. The top half of the figure shows how many hours it takes for a specified number of runs (10 to 1,000,000, across the columns) as a function of the time for each simulation run (3 to 3,000 minutes, down the rows). Networks of computers are now routinely available, so the lower half of the figure converts to an alternative metric: how many computers are needed to execute the specified number of simulations within a reasonable time limit (one week).

The number of exploratory modeling cases expands quickly as the number of variables and values rises. Such large numbers can easily tax the computation limits of even large networks of modern computers. Although most simulations are “fast” when running a single case, execution time becomes critical when exploratory modeling requires that thousands of cases be run. Thus, the art of exploratory modeling is being able to limit the analysis to the most important cases. To do so, some conventional sensitivity analysis might be used prior to the exploratory modeling in order to identify important variables in the decision space.

Number of simulation runs

Minutes per simulation run	10	100	1,000	10,000	100,000	1,000,000	
3	1	5	50	500	5,000	50,000	Total hours
30	5	50	500	5,000	50,000	500,000	
300	50	500	5,000	50,000	500,000	5,000,000	
3,000	500	5,000	50,000	500,000	5,000,000	50,000,000	

Minutes per simulation run	10	100	1,000	10,000	100,000	1,000,000	
3	1	1	1	3	30	300	Number of computers to complete simulations in 1 week (168 hours)
30	1	1	3	30	300	3,000	
300	1	3	30	300	3,000	30,000	
3,000	3	30	300	3,000	30,000	300,000	

Figure 10.2—Hours or Computers Required for Simulation Runs

DOING EXPLORATORY MODELING

Apart from its dependence on the validity of the combat model itself, exploratory modeling rests on two fundamentals: experimental variables and measures of outcome.

The selection of *experimental variables* and their assigned values constitutes the experimental design for an exploratory analysis. There is no general rule for identifying the best variables or values in a given circumstance; selection depends on the nature of the problem under study and the operational experience of the analyst(s) conducting the experiment. But the ranges selected for the variables should make an analytic difference. Experimental variables come in two types. Some are quantities that can, in some sense, be controlled in the real world (e.g., the quantity of force to be applied in numbers of divisions or squadrons), whereas others represent "risks," or some uncertainty that might require some form of hedge, or "insurance."

Measures of outcome are the experimental results used to determine the relative goodness of cases. The chosen measures of outcome should be operationally meaningful to decisionmakers and, at the same time, highlight differences between the cases in the experimental design.

An example can clarify the process for and problems in conducting an exploratory analysis. Consider an exploratory analysis examining a Southwest Asia (SWA) scenario that starts with an Iraqi attack through Kuwait into Saudi Arabia. Enemy activities and allied decisions have the potential to restrict U.S. access to the theater early in the conflict. Given these potential restrictions, three different U.S. force enhancements are to be assessed.

Four of the variables in this example represent risks. Two of the four represent enemy-controlled factors (mines and chemicals), the third represents a factor controlled by U.S. allies (political access limits), and the fourth represents a risk neither fully under enemy control nor subject to U.S. choice (actionable warning time). Three additional variables represent potential U.S. force alternatives—Naval brilliant antitank (NBAT), Army brilliant antitank (ABAT), and Sea Cavalry (SCAV). These seven variables are summarized as follows:

- Mines = number of days Strait of Hormuz closed.
- Chemicals = days of effect on tactical air sortie rates and airport of debarkation (APOD) and seaport of debarkation (SPOD) unload times.
- Warning = days between day on which U.S. forces begin mobilizing (C-Day) and day on which war begins (D-Day).
- Access = base, some, less, worst, where base = NATO and Gulf Cooperation Council (GCC) access on C-Day; some = Kuwait, United Arab Emirates (UAE), and NATO on C-Day, and other GCC on D-Day; less = Kuwait, UAE, and United Kingdom (UK) on C-Day, all others except Saudi Arabia on D-Day, and Saudi Arabia on D+2; and worst = Kuwait and UK on C-Day, all others except Saudi Arabia on D-Day, and Saudi Arabia on D+4.
- NBAT = Naval-based ATACMs, 300 ship-based brilliant antitank (BAT) missiles that can be fired beginning on D-Day.
- ABAT = Ground-based BAT missile launchers stationed in the theater and 500 missiles available as soon as airlift can move missiles to the theater.

- SCAV = Sea Cavalry, ship-based attack helicopter concept providing for 1,000 sorties over the period D+0 to D+9.

A comprehensive assessment of this scenario might include an examination of various measures of outcome, but for illustrative purposes, this exposition considers only one measure—the maximum depth of penetration of enemy forces into friendly territory. Coding the measure of outcome permits rapid examination of multiple alternative cases by showing the results of several simulation experiments on a single diagram. The coding for the sample assessments is illustrated in Figure 10.3, where the darker the shading, the deeper the enemy penetration.

The encoded outcomes for 12 simulation runs are shown in Figure 10.4. Along the x axis are four different values for the access variable; along the y axis are three different values for the warning time. The values for all remaining variables are shown to the right of the illustration.

Examining Figure 10.4 in more detail highlights the fact that when there is zero warning, enemy forces penetrate deeply even under the least restrictive access constraints (no enemy mines or chemical weapons used).

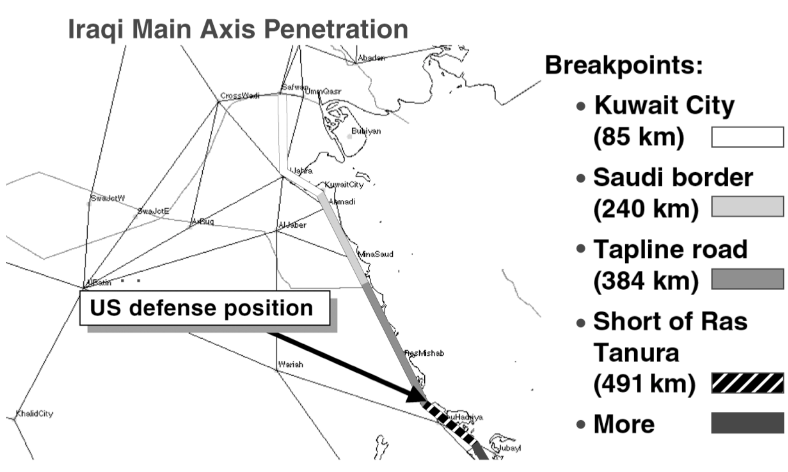
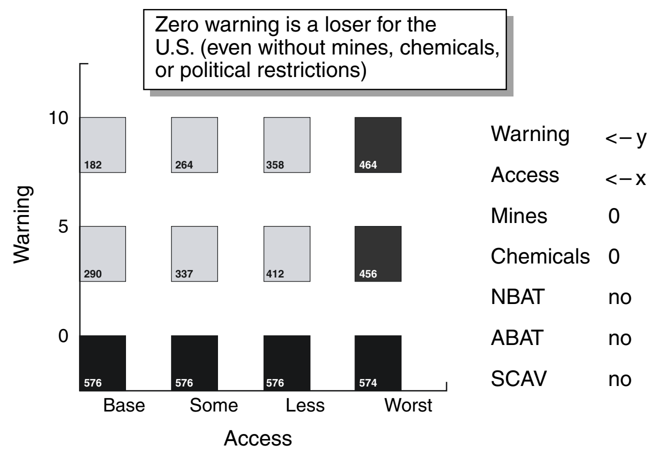


Figure 10.3—Coded Measure of Outcome



NOTE: The actual number of kilometers of enemy penetration is shown in the lower left-hand corner of each display box.

Figure 10.4—Exploring Access and Warning

Figure 10.5 introduces an additional display axis to augment the information of Figure 10.4. The shaded boxes appear to be stacked in sets of three; each set represents three different values of the mine variable along a z axis (drawn to allow the simultaneous presentation of more cases). Examining Figure 10.5 reinforces the previous observation that when there is zero warning time, the enemy forces are able to penetrate deeply.

Figure 10.6 replaces the mine variable on the z axis of Figure 10.5 with the chemical variable. Comparing the two suggests that chemicals may have a somewhat greater impact than mines do. Figure 10.7 directly compares mines and chemicals by moving the access variable to the z axis and putting chemicals and mines on the x and y axes. Here, warning time is five days.

Figure 10.7 makes it clearer that the outcomes tend to worsen faster as the chemical effects increase (as one moves to the right on the x axis) than they do as the mine effects increase (moving up on the y axis). That is, step increases in the chemical threat allow for greater

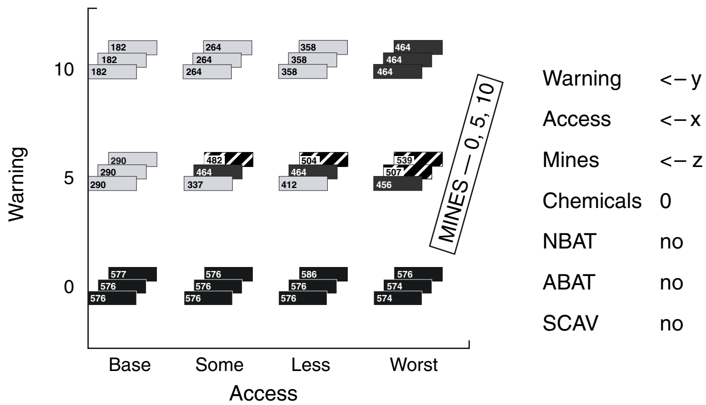


Figure 10.5—Exploring Access, Warning, and Mines

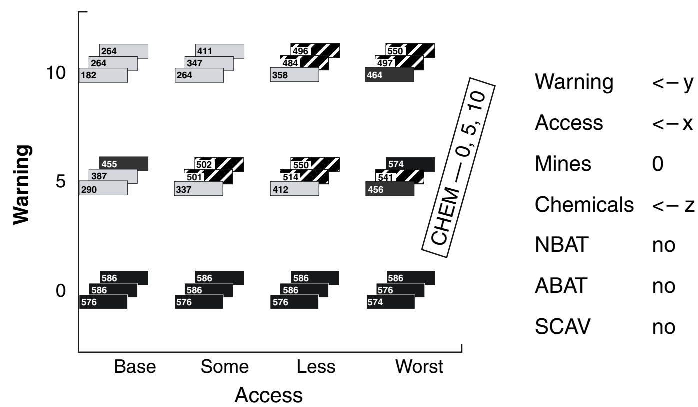


Figure 10.6—Exploring Access, Warning, and Chemicals

increases in enemy penetration than do step increases in the mine threat.

Figure 10.8 compares all three force alternatives—ABAT, SCAV, and NBAT. An examination of enemy penetration (measured in kilometers and displayed in the lower left corner of each display box) suggests that the ABAT or SCAV option restricts enemy penetration far

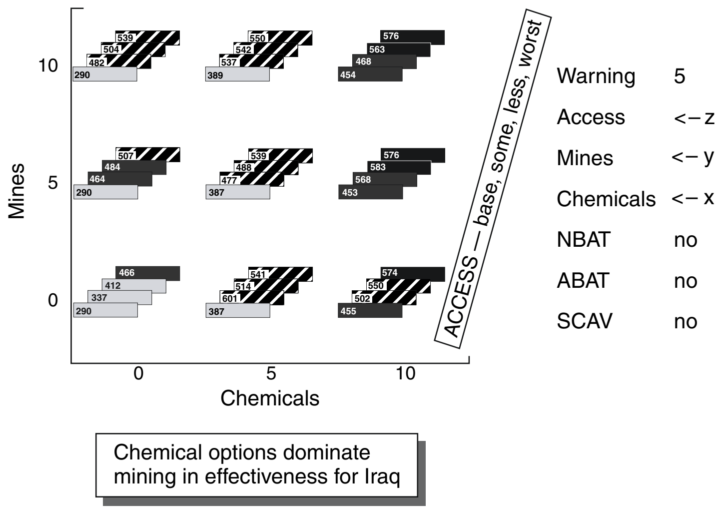


Figure 10.7—Exploring Chemicals, Mines, and Access

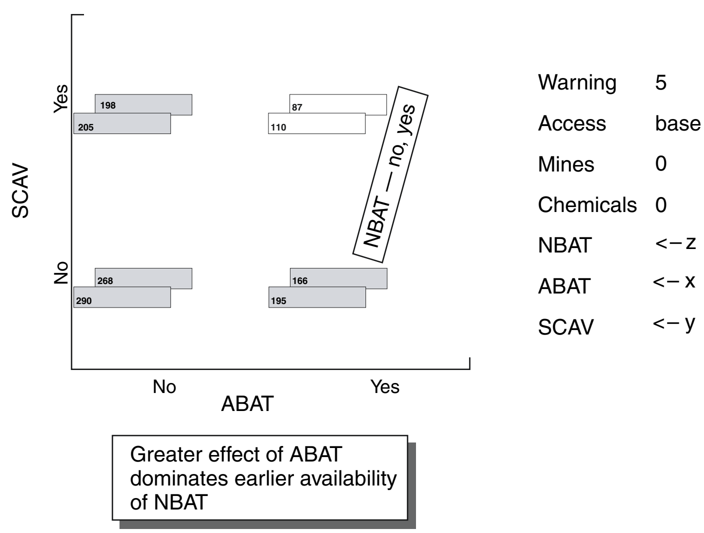


Figure 10.8—Exploring ABAT, SCAV, and NBAT

more than the NBAT option does. If the display box in the front lower left of Figure 10.8 is taken as a base case, NBAT alone reduces enemy penetration by roughly 20 km (comparing the front and rear display boxes in the lower left). ABAT alone saves 90 km (comparing the front boxes in the lower left and lower right); SCAV alone saves 80 km (comparing the front boxes in the lower left and upper left). The greater effect of ABAT offsets the earlier availability of NBAT.

Figure 10.9 illustrates how robust the ABAT and SCAV options are under the stress of enemy chemical actions. Comparing the two (i.e., comparing the three values in the display boxes in the upper left with the three values in the boxes in the lower right) suggests that they reduce enemy penetration to a similar degree.

Looking at the three values stacked along the z axis of Figure 10.9, one can see that the advantages of ABAT and SCAV are reduced when the enemy uses chemical weapons. At worst, the enemy penetrates 550 km. If both ABAT and SCAV are available (display boxes in upper right), the outcomes are substantially improved over those from either option on its own, suggesting that the two reinforce each other.

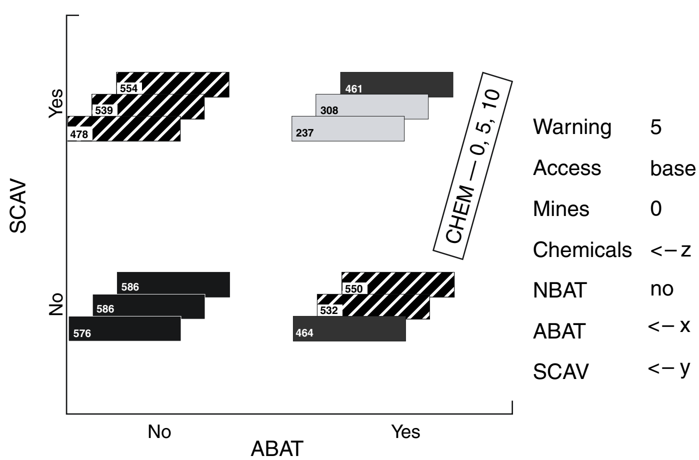


Figure 10.9—Exploring ABAT and SCAV When Chemicals Are Used

Figures 10.4 through 10.9 represent just a few of the exploratory analysis displays possible with this experimental design. In practice, any of the experimental variables can be displayed on the x, y, and z axes, and any variable not on an axis can be set to any desired value. In addition, any of the collected measures of outcome can be displayed. The figures provided here represent just one possible line of exploration through the experimental space.

THE VALUE OF EXPLORATORY MODELING

Exploratory modeling not only examines risks and force alternatives; it also can be used to test the effect of alternative theater concepts of operation (CONOPs) and alternative investments in mobility (e.g., prepositioning ashore, prepositioning afloat, and greater numbers of mobility ships or aircraft). Additionally, it permits a more extensive assessment of the U.S. force structure's robustness by making it possible to examine the many factors that might make the U.S. defense case more difficult (e.g., insufficient warning, a lack of allied contributions, unanticipated enemy strength, shortfalls in critical ammunition).

Some of JICM's features make it particularly suitable for exploratory modeling at the theater level. They include the breadth of scenarios that can be represented, the ability to address strategic mobility, and a flexible war plan system that permits many variations of the basic cases to be created.

Another advantage of exploratory modeling is that it is not limited to theater combat problems. It may be applied wherever a suitable simulation model can run all the cases in an experimental design in a reasonable time. Thus, for example, it is suitable for analyzing smaller-scale contingencies in which combat outcomes may not be the defining feature, environmental degradation, or traffic management.

Regardless of the problem to be studied, a key advantage of exploratory analysis is the ability to model both uncertainty—by using variables to represent things not under decisionmakers' control—and alternative choices. In using a model, the analyst is forced to organize all thoughts about the problem. An exploratory analysis can provide a rich illustration of the effects alternatives will have under varying circumstances, thus permitting a full appreciation of the choices.