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# Analysis, Analysis Practices, and Implications for Modeling and Simulation

Paul K. Davis, Amy Henninger

Prepared for the Office of the Secretary of Defense

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## Preface

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This paper was prepared for a Department of Defense (DoD) project directed by the Office of Program Analysis and Evaluation (PA&E) and sponsored by the Defense Modeling and Simulation Office (now the DoD Modeling and Simulation Coordination Office [M&S CO]). That project is supporting development of DoD's Analysis Modeling and Simulation Master Plan (AMSMP), which will reflect needs for modeling and simulation (M&S)\* of the "analysis domain," i.e., the domain of defense-planning functions, such as capability assessments and program analysis. Separate master plans are being prepared for the acquisition, experimentation, training, (operational) planning, and testing domains.

The Institute for Defense Analyses (IDA) has led the effort with participation by the RAND and MITRE Corporations. The project has involved white papers, workshops informing the iteration of those white papers, and a draft master plan. The present paper (one of the white papers) relates to DoD-level *analysis, analysis practices, and implications for M&S*, or what may be referred to simply as *methods*. Other white papers address *tools*—i.e., M&S for traditional warfare, M&S for nontraditional warfare, data, and technologies for M&S.†

As discussed in Appendixes A and B, this paper benefited from stimulating working-group deliberations in two workshops, held March 14–16, 2006, and June 26–27, 2006. The former was comprised largely of invited representatives from government and federally funded research and development centers; the latter highlighted suggestions from invited industry representatives. Although we benefited from these interactions, we are solely responsible for this paper's final content. Comments are welcome and should be addressed to the senior author, Paul K. Davis (pdavis@rand.org) at the RAND Corporation. Amy Henninger is with the Institute for Defense Analyses.

The RAND portion of the research presented here was conducted within the Acquisition and Technology Policy Center of the RAND National Defense Research Institute, a federally funded research and development center sponsored by the Office of the Secretary of Defense, the Joint Staff, the Unified Combatant Commands, the Department of the Navy, the Marine Corps, the defense agencies, and the defense Intelligence Community. For more information on the center, contact the Director, Philip Anton, who can be reached by email at

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\* In this paper, we use M&S to mean modeling and simulation or models and simulations, depending on the context.

† Portions of the research reported here were developed in connection with a National Academy study (National Research Council, 2006) and a study on military decisionmaking (Davis and Kahan, forthcoming). As a result, some of the material is similar in those publications and the present paper.

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## Summary

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### The Challenges

This paper proceeds from an *analysis-centric* perspective, asking what should be emphasized in M&S so as to help provide future policymakers with insightful analysis informing investment choices within and across joint capability areas. Many of DoD's analytic needs are long-standing, as is work to develop and improve supporting M&S. Some needs, however, are newer and present special challenges particularly relevant to the complexities of modern military operations. Those special challenges are summarized in Table S.1. They include increases of scope, notably addressing what DoD calls traditional, irregular, disruptive, and catastrophic conflicts; the proliferation of nuclear states; and DoD's role in homeland defense. They include new planning paradigms, notably capabilities-based planning, effects-based operations, and network-centric operations. They also include technology-sensitive considerations, such as developing systems of systems (SoS) and capabilities for information operations (IO). Although we touch upon issues, primarily in connection with networking, we do not do them justice. They are, however, treated elsewhere as problems for the acquisition and operations communities. The first six challenges, those of scope and planning paradigms, are the focus of this paper.

Taken as a whole, the table reflects the fact that warfare is moving beyond the relatively well understood phenomena that can often be treated by "physics models" into the less understood area of human behavior and how to affect it.

The following are the special challenges for DoD analysis (the challenges highlighted appear to us to be the most demanding of attention, although many others exist):

#### *Scope*

- full-spectrum planning: traditional, irregular, disruptive, and catastrophic conflicts
- strategy for a world with more proliferated nuclear weapons
- DoD support for homeland defense.

#### *Planning Paradigms*

- capabilities-based planning (CBP) for dealing with profound uncertainty
- effects-based operations (EBO)
- network-centric operations.

*Technology-Driven Considerations*

- systems of systems (SoS)
- information operations (IO, which is not treated further in this paper).

**Functional Requirements**

Given these challenges for analysis, what are the implications for M&S? Our conclusion is that *the priority should be on meeting the following functional requirements for M&S:*

1. Routine and perceptive treatment of uncertainty, including deep uncertainty.
2. Emphasizing flexible, adaptive, and robust strategies (FAR strategies).
3. Adaptive models able to evaluate candidate FAR strategies (i.e., models that represent adaptation of commanders to circumstances).
4. Adopting a family-of-tools approach that includes human-in-the-loop tools.

This list has a logically deductive flow. Because reliable prediction is often simply not in the cards (after all, our analysis must deal with complex adaptive systems), planning under uncertainty implies an emphasis on FAR strategies. To assess such strategies, we must use *exploratory* analysis supported by a special class of M&S suitable for varying a myriad of assumptions.\* Moreover, we cannot expect fully computerized M&S to do the job because they are simply not yet competitive in many cases with human war games and expert judgment. This is so particularly in efforts to understand potential effects in “PMESII space”—i.e., the space of interacting political, military, economic, social, infrastructure, and information factors. The limitations of traditional M&S lead us to a *family-of-tools approach* that includes a prominent role for humans. The approach contrasts markedly with associating analysis with constructive, rather than virtual or live, simulation.

Table S.1 shows some of the many possible tools or instruments that can be employed, each of which has different strengths and weaknesses. The evaluations, shown as cell shadings in the table, depend on many assumptions; counterexamples can be found for all of them. Nonetheless, the basic story conveyed is correct in the aggregate. Starting with the first row, relatively simple models (e.g., many spreadsheet models or their equivalent in other high-level languages) can be easily understood and explained; they may be exercised easily to quickly vary a broad range of assumptions in a systematic exploratory analysis. That is, they are agile. They are also “personal”—i.e., they can be used and adapted directly by the relevant analysts. The value of relatively simple models is as great today as it was at the advent of operations research,

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\* Exploratory analysis (Davis, 1994; 2003b) examines the behavior of a model or ensemble of models across the full space of input-parameter values. It differs fundamentally from ordinary sensitivity analysis, which usually assumes a base case and then varies inputs one at a time. Exploratory analysis assumes no base case (except perhaps for comparison purposes) and varies all parameters simultaneously. This is most practical with low-resolution models with relatively few parameters. Exploratory analysis may be parametric or probabilistic.

**Table S.1**  
**Relative Merits of Illustrative Items in a Family of Tools**

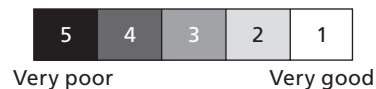
Instrument	Relative Strength						Examples
	Resolution	Analytical		Scope	Phenomenology		
		Agility	Transparency		Physical	Human	
Simple models	Low	1	1	5	5	5	START, CAPE, EXHALT, many unnamed
Big strategic simulations	Medium	3	3	2	4	5	THUNDER, ITEM, JICM, JWARS
+Adaptive models and MRM for EA	Medium	2	2	1	3	2	Enhanced versions of above
Simple ABMs	Low	3	5	5	3	4	Models built with Isaac or MANA
Advanced, "rational" ABMs	Low	2	3	5	3	2	Models built with Repast, RAND-SEAS, GA-MANA
Detailed models	High	5	5	5	1	5	Janus, JCATS, NSS
Human war gaming	Mixed	2	5	5	3	2	
Historical analysis	Mixed	5	3	5	2	1	
Field experiments	High	5	4	5	2	2	

NOTES: The shading depends on many implicit assumptions. The key point is that instrument classes have different virtues.

ABMs: agent-based models.

MRM: multiresolution modeling.

GA-MANA: a model built with MANA using genetic algorithms.



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systems analysis, and policy analysis a half century or more ago. Such models, however, have limited scope and do not represent either physical or human phenomenology except in the most abstract terms. In contrast, looking at the last four rows, detailed models (e.g., entity-level simulations), human war gaming (including seminar games, larger and more formal games, perhaps supported by simulations in the background, and human-in-the-loop work with simulations), historical analysis, and field experiments have complementary characteristics: They are hardly agile and are often not easy to understand fully, but they can provide rich descriptions of both physical and human phenomena, including those associated with complex adaptive systems (albeit with substantial attendant uncertainties).

Big strategic simulations (in the second row of the table) are heavily used because they have substantial breadth and moderate agility. In this context, they usually have no human in the loop. Their breadth makes them very suitable for integrative joint work involving multiple services and allies in theater or multitheater contexts, as in total-force planning or analysis of capabilities for particular defense-planning scenarios. They describe physical events only in very aggregate terms, however; and they do not currently represent human phenomenology well, which limits their applicability for studying the complexities of, say, counterinsurgency and

stabilization operations, or of various efforts to deter, dissuade, or coerce adversaries. Finally, they are excessively complex for studying particular mission-level or capability-area issues.

Significantly, such strategic simulations can in principle be a notch more powerful, by adding to them adaptive submodels representing commanders and group behaviors, and by using them not to examine particular scenarios in detail as is customary today, but to conduct exploratory analysis within scenario classes as well as within a given class. The mechanisms for adaptation can include “agents” as submodels, but also game-theoretic algorithms, control theory, or various operations-research methods. Were the strategic simulations more modular, individual modules could be used in studies of particular missions or capability areas.

Continuing, “simple ABMs” refer to simple agent-based models, which have become quite significant in the past decade. These models are rather agile and have moderate ability to represent human phenomenology and inform issues of command and control, but they typically have narrow scope and are otherwise quite limited—in part because they have been developed by people studying how even simple low-level behavioral rules can lead to higher-level emergent phenomena. That emphasis has been accompanied by a suppression of many issues considered critical to higher-level military analysis, such as top-down direction. More sophisticated agent-based models (the next row of Table S.1) can include a mix of top-down and bottom-up features, better physical simulation, and algorithms for making “rational” decisions and explaining those decisions, and these can then be included in high-quality physical simulations. Good abstractions of such sophisticated ABMs would be ideal candidates for the adaptive submodels postulated above for advanced strategic simulations.

Although lip service is often paid to the family-of-tools concept, and resources are sometimes used to inform and calibrate relatively aggregate models from more detailed models, analytical organizations often tilt toward investment in big constructive simulations. We conclude that *DoD and service analytical organizations should adjust their implicit investment portfolios to greatly increase the efforts to make use of simplified or specialized models suitable for exploratory analysis, human gaming and other use of experts, and empirical research drawing on history, training, and real-world operations planning.*

## Priorities for Investment and Action

The text of the paper includes many relatively detailed suggestions on how to improve treatment of uncertainty, use human gaming and experts, and apply agent-based modeling. It suggests methods for better integrating and consolidating some of the big simulations currently used in DoD’s strategic planning. The reader is urged to look at these suggestions, as well as this short summary. Table S.2, however, provides condensed recommendations and priorities for investment, along with rough estimates of costs. Our rationale for the priorities is that the items chosen represent DoD public-good investments. These public goods include, e.g., efforts to *synthesize* disparate strands of ongoing research and provide primers that make sense of inherently complex new challenges. Table S.2 recommends actions in three classes, *all* of which are critical. Within each class, we reluctantly indicate some relative priorities, but they depend on dubious assumptions. Final investment decisions should be made in a context of alternative



**Table S.2**  
**Summary Recommendations for DoD-Level Investment**

Action Class	Policy Action		Investment	Sponsor/Rough Cost Estimate
Routine treatment of uncertainty, including deep uncertainty	Analysis should emphasize evaluation of alternative strategies for potential flexibility, adaptiveness, and robustness	1	Increase openness, competition, agility, and capability, including for broad, low-resolution exploratory analysis, by (1) integrating and improving existing models to achieve a single, integrated, and very modular multiresolution campaign model; and (2) spinning off or developing separately small, specialized, and readily modified models. Establish cross-calibration with service models. This constitutes a new “business model”	PA&E/\$3–\$4M over two years, but with a net savings over time
		1	Generalize and expand current exploratory analysis methods and tools for portfolio work so that related choices can be robust to uncertainty about underlying assumptions about scenarios, category weights, risks, costs, etc.	M&S CO, AT&L, PA&E/\$1M over two years initially. Later, \$2M for creating products
Routine treatment of complex human and social issues (all PMESII dimensions)	Require study components such as gaming, red teaming, use of experts, and use of model families representing all PMESII dimensions	1	Develop consolidated primer on use of gaming, red teaming, and use of experts for higher-level DoD analysis, and for connecting results to M&S. This should include in-depth discussion	M&S CO/\$1M–\$2M for a cooperative effort of two organizations over two years
		3	Commission report drawing upon community knowledge to recommend new VV&A guidelines focused more on exploration than prediction	M&S CO/\$250K
Adaptiveness of M&S for PMESII issues and network environment	Require that models permit optional human play or insertion of results of PMESII-rich games	1	Develop review paper covering adaptive modeling methods relevant to higher-level DoD work. This should cover agent-based models, control theory, game theoretic, and other operations research methods	M&S CO/\$500K
		2	Experiments on PMESII-sensitive model-and-game families, aspiring to well-established relationships among low-, middle-, and high-resolution models	M&S CO/\$1M–\$2M over two years, covering at least two efforts
		2	Develop primer on effective use of human-in-the-loop analysis with simulations of varied resolution and character	M&S CO/\$1M–\$2M for a cooperative effort of two organizations over two years
		2	Commission competitive design for new or substantially reprogrammed campaign and mission-level models built around network centrality (and degrees thereof). Priority 2 only because of high cost	Joint Staff/\$2M for industry competition and review. \$5M–\$40M eventual cost, assuming reuse

NOTES: The number column indicates the relative priorities within each category. AT&L = Acquisition, Technology, and Logistics.

budget levels over time and an understanding of what can and will be funded through other channels. To put it differently, Table S.2 omits many high-priority investment items—e.g., in advanced agent methods to assist in modeling and analysis of culture-sensitive issues, only because they are *apparently* being pursued by the services, commands, and defense agencies. The Office of the Secretary of Defense should ensure that this is true and, if it is not, arrange for changed priorities. Much of the work needed is in the province of science and technology and, thus, of the Director for Defense Research and Engineering.

Within the first action class (treatment of uncertainty), the first recommendation is complex, calling for improvement of big models *and* support of simpler models (often specialty models) *and* assuring the ability to compare the models. *This recommendation, taken as a whole, corresponds to a distinctly new business model for DoD-level investment.* As a whole, the need exists for greater openness, competition, agility, and capabilities. Past investment has tended to emphasize standardization and the predictable result has been to generate models and modeling activities that are good at what they do, with consistent data, but that lack the vigor, creativity, and cross-cutting flexibility that is needed. DoD should on the one hand integrate and improve its current strategic models (potentially having only a single high-level simulation for core work, with broad coverage and either links or relationships to more detailed models as needed for particular analyses). DoD should make the result as modular as possible and actively plan continuing competition and evolution at the module level. Different module versions will likely be superior in different analyses, whether because of resolution or what phenomena need to be represented well. Some module versions might allow for optional human play or might be tuned to recent empirical information. DoD should, on the other hand, also encourage and use more relatively small “specialty” models, whether for agile aggregate-level work or for very narrow analysis of mission capabilities—analysis unencumbered by the weight of full campaign models. Investments to develop tools for and skill in *rapid* development of such specialty models will also be needed. The tools could range from those akin to MATLAB<sup>®</sup> to those more like the tools of the Defense Advanced Research Projects Agency’s (DARPA’s) RealWorld program. DoD should also invest modestly to ensure that researchers are able readily to compare assumptions and results of, e.g., the specialty models and relevant big-model modules. In some cases, a specialty model may be identical, except for programming language, to a big-model module; in other cases, there may be important and desirable, but optional, differences. Similarly, cross-comparison mechanisms should exist to ensure that DoD’s integrated campaign model has understood relationships with relevant service-level models.

This recommendation is complex, but we urge honoring its complexity rather than investing only, for example, in the consolidation and integration of current strategic models for the sake of greater efficiency and standardization.

The second recommendation is to generalize the concepts of “exploratory analysis” for effective application in portfolio analysis—e.g., analysis to inform resource allocation within a capability area or across multiple capability areas. The allure of portfolio methods is considerable, but the results are often bogus because they depend too sensitively on low-level assumptions. As with capabilities analysis generally, the solution is to seek flexible, adaptive, and robust strategies of investment, which requires analysis in which the assumptions affecting the resource-allocation decisions are systematically and simultaneously varied.

Within the second action class (routine treatment of complex human and social issues), our primary recommendation is for DoD to develop an integrative primer on the use of methods such as red teaming, war gaming, and use of experts. This class of issues is ripe for coherent synthesis, which is not an effort for a committee. We also mention the need to revise policies on verification, validation, and accreditation (VV&A) so that they acknowledge and deal sensibly with the vast array of models (and associated data) that is simply not “predictive” in the classic sense, but rather is intended for more exploratory work amid uncertainty. This work can build on the substantial base of VV&A material developed by M&S CO over the past decade.

Within the third action class (adaptiveness and networking), we again recommend a synthetic activity, starting with one that pulls together methods such as agent-based modeling, control theory, and game theory so as to clarify which methods for providing adaptiveness are most suitable. We also recommend recognizing that a new generation of strategic/operational-level model is needed for the network-centric era. Even JWARS (now called JAS)<sup>2</sup> has only some of the features needed, and no consensus yet exists about what a new-generation model might look like. This suggests the need for preliminary research and a competition of ideas. This is distinct from and in addition to network-centric models necessary for design and evaluation of particular systems of systems, which are of great importance within the acquisition community.



## Acknowledgments

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We acknowledge the many valuable suggestions provided by participants in two workshops held as part of the project (see Appendixes A and B), as well as by various colleagues at RAND, IDA, and MITRE. Dell Lunceford and Edward Harshberger were kind enough to provide thoughtful and detailed formal reviews.



## Abbreviations

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ABM	agent-based model
AT&L	Acquisition, Technology, and Logistics
CAA	Concepts Analysis Agency
DIME	diplomatic, information, military, and economic
DoD	Department of Defense
EA	exploratory analysis
EBO	effects-based operations
FAR	flexible, adaptive, and robust
FFRDC	federally funded research and development center
IDA	Institute for Defense Analyses
IO	information operations
JFCOM	Joint Forces Command
M&S	modeling and simulation or models and simulations, depending on the context
M&S CO	DoD Modeling and Simulation Coordination Office (formerly the Defense Modeling and Simulation Office)
MS&A	modeling, simulation, and analysis
MRM	multiresolution modeling (allowing inputs to be made at different levels of resolution)
MSG	massive scenario generation
NCW	network centric warfare
OSD	Office of the Secretary of Defense

PA&E	Program Analysis and Evaluation
PMESII	political, military, economic, social, infrastructure, information
SoS	systems of systems
VV&A	verification, validation, and accreditation



## Introduction

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### Purpose and Scope

This paper addresses analysis and analysis practices for defense planning and their implications for modeling and simulation (M&S).<sup>\*</sup> The analysis in question is accomplished for Quadrennial Reviews and for continuing work on capability assessments, requirements analysis, and program analysis. The paper's purpose is to delineate priorities for the way ahead—i.e., for investments and other actions to ensure that future M&S will serve the needs of defense-planning analysis.

Traditionally, analysis for defense planning has been at the strategic and operational levels, but what these levels now include is unclear, given that the organization of forces is changing, low-level activities can have strategic importance, and sound assessment of capabilities sometimes requires in-depth analysis. Accordingly, the paper takes a broad view of its scope, although not adequately addressing some issues (notably related to systems of systems [SoS], personnel, training, and operations planning) that are usually seen as subjects for other communities. Future work should address the substantial overlaps that increasingly exist across the M&S-using communities.

### Perspective and Approach

Consistent with its purpose, the paper approaches issues from strongly analysis-centric and capabilities-based perspectives, rather than the perspective of modeling *per se*.<sup>1</sup> Chapter Two characterizes the new analytic problems implied by policy concerns. Chapter Three draws implications for M&S, noting both shortfalls and ways of addressing them in the near to mid term. Chapter Four discusses some of the improvement methods in more detail and suggests priorities for action and investment. Chapter Five draws some conclusions. The bibliography includes citations to relevant published literature.

Overall, the paper is ambitious, taking the view that much of what should be done to improve analysis can be done sooner rather than later. Although science and technology will continue to provide grist for further progress, *the key concepts, methods, and tools for what is needed most already exist or are well within reach*. This said, organizational inertia is a significant

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\* In this paper, we use M&S to mean modeling and simulation or models and simulations, depending on the context.

factor and assimilation of new methods and tools is always challenging. In a sense, *the issue is transformation of the analytic community.*

## Policymaker Concerns

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### Special Challenges

Many defense-planning analysis issues are long-standing and continuing. This paper makes no attempt to review them and assumes that evolutionary progress will continue to be made in improving such analysis and the M&S that supports it. Our focus is exclusively on “special challenges” and, in particular, how analysis can address major Department of Defense (DoD) themes that have emerged over the past decade, and that have been emphasized in recent high-level documents (Rumsfeld, 2006).<sup>2</sup> Significantly, it is no longer necessary to stress jointness because the requirement is now widely accepted.

The following are the themes of modern DoD planning:

#### *Scope*

- full-spectrum planning: traditional, irregular, disruptive, and catastrophic conflicts
- operations abroad and DoD support for homeland defense.

#### *Planning Paradigms*

- capabilities-based planning for dealing with profound uncertainty
- effects-based operations (EBO)
- strategy for a world with more proliferated nuclear weapons.

#### *Technology-Driven Considerations*

- systems of systems (SoS)
- information operations/network-centric operations.

### Observations About the Special Challenges and Themes

The following observations cut across the themes shown above:

1. *Complex, Interconnected Systems.* It has become crucial to understand links among the many factors at play; to apply all of the instruments of national power in a coordinated and sensible manner; and to do so anticipating that the many parties involved in conflict learn, adapt, and do unanticipated things and that other unanticipated

events will also occur.\* All of this is frequently discussed as planning for effects-based operations.<sup>3</sup> How best to conceive and then achieve desired effects is a considerable challenge for analysis. It is clear, however, that a key to meeting the challenge will be recognizing that the systems of interest are *complex adaptive systems* (CAS), and that many of the concepts from modern research on such systems will need to be applied.<sup>4</sup>

2. *Capabilities-Based Planning.* To cope with uncertainty and other challenges, DoD has shifted to capabilities-based planning (Rumsfeld, 2001 and 2006), which stresses development and honing of capabilities that can be applied to a wide range of challenges and circumstances (Davis, 2002a), and to its cousin in operations—“Adaptive Planning,” in which war plans are developed so as to anticipate and then support major changes as circumstances change. Implementation of capabilities-based planning is a difficult undertaking—in part because the analytical community has been so wedded to in-depth analysis rather than analysis under uncertainty. Although force transformation is sometimes treated as a separate issue, many of DoD’s efforts at transformation (see <http://www.oft.osd.mil/>, as of December 19, 2006) relate closely to both capabilities-based planning and the next item, networking.
3. *Networking.* The ascendancy of ubiquitous networking in all DoD activities is often referred to as moving to network-centric operations. The advent of networking also increases the scope and importance of information operations (IO) and revolutionizes many aspects of command and control. Unfortunately, it remains difficult to represent network-centric issues appropriately in analysis. Although it is easy enough to represent discrete platforms and communication links, it is not so easy as yet to reflect such core considerations as publish and subscribe, self-synchronization, or the capability to modify and adapt command, control, communications, computers, information, surveillance, and reconnaissance (C4ISR) networks substantially in the course of operations, sometimes linking entities that had not been expected to be operating together.<sup>5</sup> The same difficulty arises in designing and evaluating systems of systems, a key challenge for acquisition. System of systems work is also crucial in much of the social-networking analysis relevant to DIME/PMESII issues.
4. *Nontraditional Warfare.* Because U.S. military prowess in traditional combat has become overwhelming, adversaries have been avoiding direct engagements, instead resorting to “irregular” warfare; moving installations underground or otherwise seeking to frustrate overhead surveillance and precision targeting; mingling with the civil population; or attacking the United States, its allies, and their interests at home. The global war on terrorism is but one face of this challenge.
5. *Stabilization and Reconstruction.* The U.S. military has not traditionally been enthusiastic about stability and reconstruction missions, but—as highlighted in the recent Quadrennial Defense Review—they may well be a major element of military opera-

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\* In DoD’s acronym-loving fashion, it refers to political, military, economic, social, infrastructure, and information (PMESII) factors and diplomatic, information, military, and economic (DIME) instruments.

tions over the foreseeable future. Success in these missions, without the benefit of overwhelming presence of forces, poses daunting challenges.

6. *Homeland Security*. Although we do not discuss the issue further in this paper, homeland security M&S challenges have become very important.

The significance of these observations can perhaps best be appreciated by contrasting the types of questions posed to analysts in the previous era and today. Appendix C provides such a contrast.

## Implications for Analysis, Modeling, and Simulation

It follows from the demands described above that a number of key *functional needs* can be identified for analysis and supporting M&S. These include:

1. *Routine and Perceptive Treatment of Uncertainty, Including Deep Uncertainty*. Uncertainties are profound regarding future conflicts, the circumstances of those conflicts, and the complex effects of actions taken within the conflicts. Further, major changes will occur over time, affecting national priorities and defense programs. Thus, analysis and M&S must deal well with uncertainty and, as part of that, must characterize risks well.
2. *Emphasizing Flexible, Adaptive, and Robust Strategies (FAR strategies)*. Because planning and operations are so heavily affected by uncertainty, with accurate prediction often being implausible, strategies need to be flexible, adaptive, and robust (FAR strategies). Candidate strategies must therefore be evaluated across a broad possibility space.<sup>6</sup>
3. *Adaptive Models and Rapid Model Development*. Evaluation of adaptive strategies requires adaptive models. That is, if strategies are conceived with branches and other features to cope with uncertainty, their evaluation will *require* models that generate realistically dynamic circumstances with which strategies are to deal, and that represent the strategies' intended adaptations. Such models will need to reflect the learning, adapting, and sometimes random acting of individual groups, and also the possibility of structural changes in the nature of the system as coalitions form or dissolve, key leaders emerge or disappear, and physical events change realities of, say, geography or access.<sup>7</sup> Since not all the adaptations can be anticipated in advance, it will also be important to make rapid changes in models and to develop quickly small specialized models or submodels.
4. *Reinserting People in M&S and Related Analysis*. For dealing with uncertainty, introducing innovative concepts, or working across boundaries such as those associated with DIME and PMESII, people are exceedingly capable—much more so than traditional M&S. Because of this, gaming is often a preferred method for operational planners and strategic planners.<sup>8</sup> The same human advantages are needed in M&S,

in which optional human-in-the-loop simulation can be quite useful. Reinserting people can be accomplished as discussed in a later chapter.

These needs are not merely nice to have; rather, they lie at the core of whether decisionmakers are to be well served.

## Dealing with Uncertainty and Risk

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### Introduction

The most important step in dealing well with uncertainty is acknowledging its many dimensions and their magnitude. Doing so is a core element of capabilities-based planning. In recent years, the Department of Defense has come a long way, moving from an era in which only one or two scenarios were taken seriously to one in which planning guidance describes in some detail quite a number of substantially different name-level challenge scenarios. Many of these are examined with considerable care by the Office of the Secretary of Defense (Program Analysis and Evaluation) (OSD [PA&E]), J-8, and the services' analytical shops in support of force planning. The next step is for analysis to routinely and systematically examine capabilities for each such name-level scenario across the range of possible circumstances (including creative strategies and tactics by both sides). That is, *exploratory analysis* is needed for each name-level scenario (Davis, 1994, 2002a, and 2003b), as well as across them.\* To illustrate the need, consider how the operations in Afghanistan and Iraq have stressed U.S. force structure in ways very different from those assumed in force-planning scenarios used in earlier years. Before the invasion of Iraq, operations planners had to consider many possible plan variants, and what developed still had unexpected features.<sup>9</sup> Good capabilities analysis, then, requires broad exploration.

### Strategic Adaptive Planning

#### Overview

One aspect of planning for adaptiveness is seeking capabilities that will prove valuable for many missions and circumstances. Another aspect is *strategic adaptive planning*, by which we mean pursuing capability-development programs that are expected to change over time as information is gained about the future security environment, what can actually be achieved

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\* Exploratory analysis (Davis, 1994; 2003b) examines a model's behavior across the full space of input-parameter values. It differs fundamentally from ordinary sensitivity analysis, which usually assumes a base case and then varies inputs one at a time. Exploratory analysis (EA) assumes no base case (except perhaps for comparison purposes) and varies all parameters simultaneously. This is most practical with low-resolution models with relatively few parameters. EA may be parametric or probabilistic.

technologically, how alternative approaches to achieving the capabilities compare, and the preferences of political leadership. In this approach, a capabilities-development program may begin with competitive ideas carried forward through more detailed concept formulation and even experimentation (perhaps with prototypes). Later, the program may largely focus on a particular path, but it may be hedged by carrying along alternatives at a lower rate of expenditure. If appropriately funded and executed, evolutionary acquisition is an example of strategic adaptive planning.

### **An Example in Industry: Real-Options Theory**

One tangible example of deliberate strategic adaptive planning can be seen in “real-option planning” in industry. To be sure, there are stark differences between industrial planning and defense planning. The most obvious is that companies are focused primarily on a single measure—future profit—whereas the DoD has many objectives to pursue, which tend not to be readily commensurate, much less in something as simple as dollars. Further, some industries have the great advantage of being able to base risk-assessment analysis on rich historical and developmental databases, such as those of the financial markets over the past century, or those of aircraft designers over the past 50 years. Some of DoD’s risks are different in character than those found in industry. So, yes, there are big differences.

Nonetheless, the practice of real-options theory is a good example of strategic adaptive planning. Its success in some large companies is an existence proof that such planning can be done, that chief executives are both interested in and willing to invest on the basis of risk-and-opportunity balancing considerations, that such investments can be informed by “hard” analysis, and that the payoffs can be very large.<sup>10</sup>

In business, the real-options issues may include, e.g., deciding whether to invest in variants of a product’s principal design or in alternative products. If these are assessed with only best-estimate assumptions about the future, they may have little apparent value, but if assessed with recognition of uncertainty about future demand, success of the principal design (and the options), and various possible competitors, such options may have *substantial* value. The net effect is that some investments create or maintain options that hedge against bad futures and/or prepare to exploit good opportunities.

Parallels exist in the defense context. The Missile Defense Agency (MDA), for example, is seeking to develop ballistic missile defense systems that may be used for very different missions (e.g., homeland defense versus defense of an ally’s capital or of forward-deployed U.S. forces) against adversary systems that may have very different countermeasure characteristics. Further, the objectives for ballistic missile defense systems in the future may change drastically as a function of political leadership, the nature of the strategic environment, and what proves feasible.

In such a context of uncertainty, MDA’s program arguably needs to be adaptive enough so that the requisite technology is pursued to deal with as much of the possibility space as possible, given constraints of budget and technology. In practice, this implies investing in a range of options—but also with the expectation of assessing progress on these options over time and then *choosing*—i.e., killing off some that fail to develop successfully so as to pay for those that are more successful and that appear increasingly appropriate with time.



### Examples in Social-Policy Studies

Another approach to strategic adaptive planning is represented by work on policy responses to perceived trends of global warning, and in studies of very long-term social issues (Lempert, Popper, Bankes, 2003). The authors have variously referred to their approach as exploratory modeling and robust adaptive planning. The philosophy of the work has much in common with real-options planning, but the mathematical and analytical methods are quite different.

### Obstacles

At least three obstacles exist to having exploratory analysis in various forms available routinely as part of defense planning: (1) the current analytical infrastructure and its familiar routines, (2) antipathy to uncertainty analysis, and (3) the paucity of analytical models and methods needed for exploratory analysis. A few words on each of these are warranted.

1. *Familiar Routines.* In the DoD, falling into familiar routines translates into placing great emphasis on conducting in-depth analysis on defense-planning scenarios, with models that the services accept, and with databases approved by the services or other authorities. Achieving this is laudable as a baseline and, indeed, is a considerable achievement since it promotes integration and facilitates apples-to-apples comparison of study claims. Unfortunately, current execution leaves little time for more far-reaching investigation away from the comfortable approved baselines. Policy guidance urging broader parametric exploration and providing guidelines for doing so is seldom followed.<sup>11</sup>
2. *Antipathy to Uncertainty Analysis.* Many analysts describe having been admonished by their superiors that decisionmakers want best estimates presented without the complication of caveats. Such admonishments clearly occur at intermediate levels between working analysts and decisionmakers, and, sometimes, decisionmakers themselves send such messages. However, analysis that suppresses uncertainty is bad technically and ethically, as can be appreciated by reviewing classic texts and professional-society codes of practice. Furthermore, the claim about decisionmakers is a canard, because many top decisionmakers welcome discussions of uncertainty *so long as the discussions also assist in choice*. Decisionmakers have little time for what they may see as hand-wringing, paralysis, technically elegant but off-point excursions, or long lists of caveats. In contrast, when uncertainty-rich analysis assists in defining flexible, adaptive, and robust strategies—whether by “stacking decks” or planning branches and hedges—the reception will often be positive. This is true both of decisionmakers who approach problems “analytically” and of decisionmakers who are more intuitively oriented and predisposed toward particular directions, but nonetheless are interested in assuring success, which includes preparing for contingencies (Davis, Kulick, and Egner, 2005; Davis and Kahan, 2006).

This said, there are distinct limits to how much uncertainty analysis is useful and in what form it should be presented. It has been argued (Davis, Kulick, and Egner,

2005) that a suitable level of detail for bottom-line results is as shown in Table 3.1 (although, of course, it depends on further layers of reasoning that are not shown).

3. *Paucity of Models and Methods.* The third obstacle has been one of models and methods. This obstacle is discussed in the following section.

## Tools and Methods for Exploratory Analysis

A common lament by analytic organizations is that the models available to them are not suitable for far-reaching exploratory analysis; with effort, they can be used to do numerous excursions around baseline cases, but going beyond that is painful, time-consuming, and expensive. As discussed earlier in the paper, simpler, faster-running models are desirable for agility and breadth (i.e., for exploratory analysis). The question then arises, where can an organization find such models and establish their validity for the intended purposes? Four primary options exist, as indicated in Table 3.2.

The first of these options is attractive if one has a model designed with multiple levels of resolution in mind. In these cases, one can turn off higher levels of detail for particular modules when doing exploration and then turn them back on as needed to follow up on conclusions in more detail. Such features have been built into only some of the commonly available DoD models. Adding some such features to preexisting models is straightforward in some cases. In other cases, however, it is more difficult and requires approximations and narrowing of scope.

Whereas exploratory analysis as discussed above is usually performed with a single model, albeit one that is highly parameterized and perhaps has probability distributions to represent uncertainty, this makes sense only if the model itself is sufficiently sound. Often, we lack confidence about the model itself, referring to “structural uncertainty,” ambiguity about causal relationships, and other complications. In such cases, it is possible to represent some of the troublesome structural uncertainties with analytical tricks (Davis, Bankes, and Egner, forthcoming), such as parameterizing the form of functions and permitting certain kinds of stochastic behaviors motivated by, e.g., historical observation. Even the directionality of arrows in an influence diagram may be varied parametrically.

**Table 3.1**  
**Comparison of Courses of Action Under Uncertainty**

Course of Action	Most Likely Outcome	Best-Case Outcome	Worst-Case Outcome	Net Assessment of Course of Action <sup>a</sup>
1	Good	Good	Marginal	
2	Good	Very Good	Marginal	
3	Very Good	Very Good	Very Bad	

<sup>a</sup> Depends on the decisionmaker and the context. A conservative assessment would emphasize most-likely and worst-case columns; others would give more weight to the upside potential. If the “do-nothing” baseline (not shown) is considered utterly unacceptable (e.g., by revolutionaries), the upside potential may be the key.

**Table 3.2**  
**Alternative Ways to Create Simplified Models for Exploratory Analysis**

Approach	Description	Comments
"Freeze" many variables of a more complex model; conduct exploratory analysis on a set of key parameters <sup>a</sup>	Find or create higher-level parameters Ensure legitimacy of freezing of other variables	Feasible only in some models, e.g., those designed as top-down with multiresolution modeling techniques (MRM). For others, important uncertainties are often too deeply buried in databases
Build a new simple model <sup>b</sup>	Approach the problem top-down Build in specific hooks to higher-resolution models Parameterize extensively Allow for structural variations as well	Building simple models is easy; building good ones, which abstract properly and connect to more detailed models, is not
Build a motivated metamodel <sup>c</sup>	Start with a "trusted" complex model Hypothesize a much simpler model that is still phenomenologically motivated, but in aggregate terms Build in correction factors with unknown coefficients Use statistical methods to fit the postulated model to the behavior of the trusted model	The trusted model may not include important dimensions of uncertainty, such as adaptive decisions. If trust is justified, however, this approach can lead to reliable simple-and-fast models that also provide good explanations of the results
Standard response surface methods <sup>d</sup>	Fit behavior of trusted model to statistical regressions	Problems: trusted model may not be trustworthy; also, resulting "simple" model provides no meaningful explanation and may obscure important correlations relating to system capabilities for systems with multiple individually critical components

<sup>a</sup> Much work of this type has been done with JICM (Fox, 2003).

<sup>b</sup> Many examples exist (Davis, Bigelow, and McEver, 2000; Davis, McEver, and Wilson, 2002), although most were seen as one-time actions rather than methodology. This approach is also common in science.

<sup>c</sup> This is a synthesis of cause-effect modeling and statistical analysis (Davis and Bigelow, 2003).

<sup>d</sup> This approach is commonly taught in operations research and applied statistics.

A complementary approach that does not depend on any single model is ensemble modeling or modeling by committee (Henninger, Pratt, and Roske, 2006). The notion has been embraced by the "machine learning" community (Dietterich, 2000), which often uses the method to boost predictive utility of classifiers. The primary differences among model estimates often reflect differences in sampling (e.g., bootstrapping, bagging). The notion of ensembles has also been used by the weather-modeling community (Franklin, 2005). In this area, the models can take on distinctly different forms (e.g., statistical, dynamic). And, finally, the term "ensemble" is also used in studies of global warming and long-term futures (Lempert, Popper, Bankes, 2003).

Since nomenclature between (and within) communities can differ, comparisons can be somewhat ambiguous. That is, one person's interpretation of what can be parameterized may intersect with another's vision of what becomes an underlying assumption. Given the number of dimensions that could add to robustness of our analyses (e.g., random seeds, data sources and sampling methods, parameterization, scenarios, algorithmic implementations, underlying theoretical assumptions) coupled with the imprecision in terms, it would perhaps be prudent to synthesize related information into a cogent form.

In ensemble modeling, one starts with a set of models, each of which has its own predictions. One then combines results, perhaps with weighted sums or some other schema, in an attempt to improve the accuracy of the overall prediction. The concept is loosely based on the notion that if each model is more likely to be right than wrong, the prediction of the majority of models is also more likely to be right than wrong. Further, the probability that the correct outcome is supported by a majority of the models should be a monotonically increasing function of the number of the models in the ensemble, converging to one as the size of the ensemble approaches infinity. Combining results of multiple models is not, of course, a substitute for designing good models, but it is often not so easy to know which of many competing models is better or worse, in which case ensemble modeling can be very helpful. As a caution, however, if the individual models are more likely to be wrong than random chance, then combining results will worsen prediction.

### **Exploratory Analysis for Portfolio Work**

A final concept to mention is at the frontier of current work: “exploratory analysis of portfolios.” DoD is beginning to use portfolio methods extensively in its capabilities-based planning, but the methods and tools for doing so are only emerging,<sup>12</sup> with current work being for the Office of the Secretary of Defense (Acquisition, Technology, and Logistics). A recent conclusion of that effort is that the methods of exploratory analysis that have emerged over the past decade need to be applied now to portfolio assessments because attempting to use portfolio-analysis methods for tradeoff work is exceedingly unreliable without examining how conclusions change as a function not only of scenario, but also of weighting factors, aggregation rules, subjective judgments about different types of risk, and costs. Because of the magnitude of uncertainties and diverse nature of the factors, even the best analysts cannot easily reach sound conclusions without more far-reaching—and semiautomated—exploration. In the past, that was impossible, but it is now technically feasible. Given that policymakers are repeatedly calling for tradeoff analyses within and across the new joint capability areas, the extension of exploratory analysis to portfolio work seems to us essential. See Table 3.3.

**Table 3.3**  
**Action Items for Improving Treatment of Uncertainty and Risk**

<b>Science and Technology</b>	
Improve or develop tools to enable or simplify exploratory analysis	Modify “big” models (JICM, Storm, etc.) Build new simple models Build “motivated metamodels” Improve tools for analysis of exploratory runs
Improve and develop methods to support integrated families of models	Develop theory for cross-resolution calibration and multiresolution modeling; application to DoD’s “big-four” set of simulations
Adapt best practices from real-options theory for defense work where applicable	Mine recent industry experience for insights and methods Apply in applicable subdomains Conduct prototype studies and then build appropriate tools
Improve and field portfolio methods for capabilities analysis	Build top-down portfolio tools with multiple levels of zoom Generalize methods of exploratory analysis for portfolio work
<b>Within Analytic Studies</b>	
Specific studies	Build terms of reference that demand analysis of risk and uncertainty based on exploration and evaluation of candidate flexible, adaptive, and robust strategies



## Families of M&S Tools

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### Understanding the Issues

Although the conclusion was valid even in the allegedly “simpler days” of the Cold War, the following logic seems compelling:

*Whereas*

*Today’s special M&S challenges involve people, decisions, and behaviors;  
Current DoD M&S are poor at representing human creativity, adaptation, and variation;  
Other methods, such as human gaming and interactive simulation are better in this regard;  
and  
Much information can be had from studying real wars, operations, tests, and exercises.*

*M&S for analysis should be construed broadly so as to include these other methods.*

Doing so will involve breaking down traditional barriers. What is needed is a mix of analytical instruments and types of scientific inquiry. Such a mix would include

1. diversity of models (with varied levels of resolution, perspective, character, and degrees of interactivity)
2. human games and other exercises, structured to increase rigor and analytical content
3. laboratory and field experiments
4. other empirical work, drawing upon real-world operations planning, training, history (including lessons-learned studies), and consultation with experts in numerous disciplines and functions.

It is one thing to assert that such a mix should be used, but many questions arise, such as whether human gaming can actually assist in analysis. Some of these are discussed in subsequent sections.

Table 4.1 elaborates by contrasting strengths of some of the instruments.<sup>13,14</sup> At the top left, by simple models we mean *relatively* simple models (which may also be simulations), ranging from closed-form equations to models implemented in high-level languages, such as Microsoft Excel or Analytica. They are characterized in Table 4.1 as very good (white) for their agility





be relatively transparent.<sup>16</sup> The current versions of such models are typically not very adaptive, however, and are used to study particular approved scenarios in depth. If they were made more adaptive (as discussed in a later section), given more multiresolution features as described below, and used for broader exploratory analysis, their value could rise a notch to light gray or white.

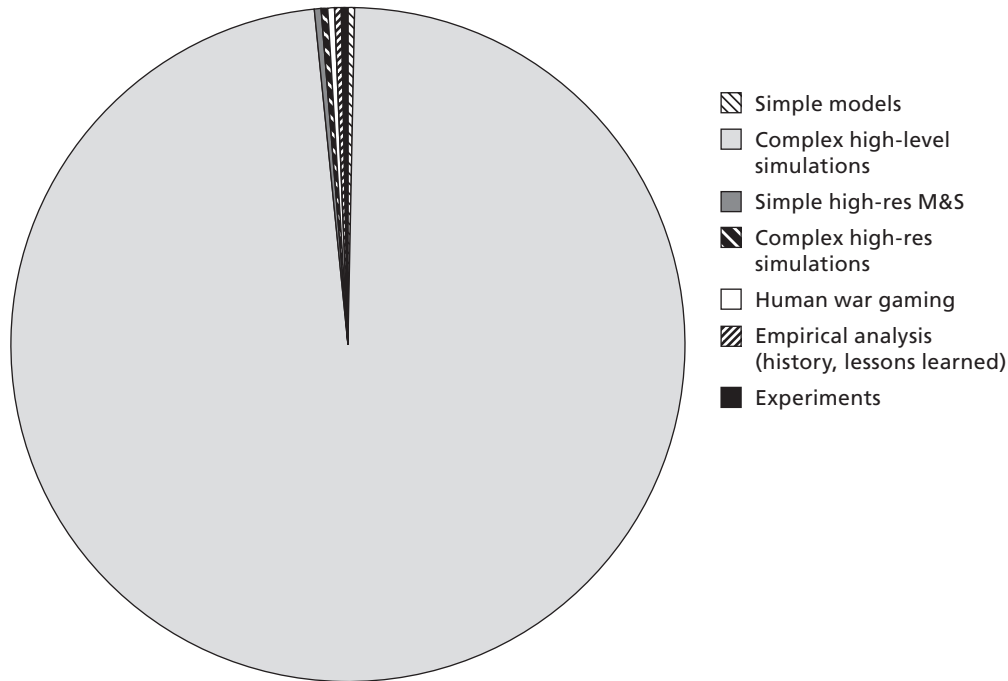
Simple agent-based models of the bottom-up variety (e.g., models based on MANA or Pythagoras) have at least moderate ability (middle gray) to explore phenomenology and human action, although analysis with them is not straightforward.<sup>17</sup> In other respects, agent-based models (ABMs) are typically quite limited. Much better agent-based models are possible and are being pursued. These may include a mix of top-down and bottom-up features, more rational decisionmaking based on balancing considerations through an objective function, etc. Detailed models (e.g., those at mission, tactical, or engagement levels) are essential underpinnings even for higher-level defense-planning work because they can represent underlying phenomena well,<sup>18</sup> motivate sound aggregate models<sup>19</sup> (e.g., the strategic simulations), and sometimes be used to calibrate them. Such models are also an essential link between the “policy and programs world” to the world of war fighters and engineers. Such models, however, are poorly suited to higher-level analysis and decision support.

Human war gaming is quite agile in the sense that a game can be quickly put together to deal with previously unstudied issues, but games are notoriously deficient in breadth, focusing on a single scenario or a few vignettes. They are, however, excellent vehicles for highlighting “real” factors in the world, including likely or possible human perceptions and behaviors. A human game, for example, will often suggest an unanticipated adversary thought pattern or an unanticipated constraint on what U.S. and allied leaders would be able and willing to sanction. Historical work is not at all agile, but it covers substantial ground. It is a rich source of knowledge about what “really” happens and what humans sometimes do and how frequently they make mistakes on the one hand, but achieve audacious success in other cases.<sup>20</sup> Other historical research provides empirical evidence of aggregate-level phenomena, which can be powerful in developing M&S.<sup>21</sup>

Although the evaluations shown are merely illustrative, depending on many underlying assumptions, the general point is valid: Much value can be gained from drawing on the multiple instruments and sources of information. It follows that analytical organizations should consciously plan to have and exploit the full range of instruments and forms of inquiry.

*Taking a Portfolio Approach to Investments in M&S for Analysis.* This reasoning suggests that in the years ahead DoD’s *analytical organizations should design their analysis and supporting research with an explicit portfolio approach*, i.e., investing in a *range* of instruments. Figure 4.1 characterizes schematically the current investment portfolio of many military analytical organizations. Our assertion (without reliable empirical basis and perhaps exaggerated slightly<sup>22</sup>) is that the current de facto portfolios are extremely distorted in favor of high-expense, relatively detailed simulations. The figure also notes explicitly that, in the broader view attempted in this paper, analysis is not equivalent to modeling and simulation, and M&S is not equivalent to simulation.<sup>23</sup> The behavior of M&S organizations, however, suggests that only simulation survives at budget time.<sup>24</sup>

**Figure 4.1**  
**Current Investment Portfolios of M&S Organizations**



RAND OP176-4.1

That analysis is not equivalent to M&S, and certainly not to simulation, helps to explain why there has sometimes been a tension between M&S groups and analysts not in such groups. Higher-level analysis depends on agile work cutting across boundaries and addressing a broad range of issues. That is often a poor match for data-intensive simulation activities, especially those that depend for their success on complex, consensus-seeking, and lengthy interactions across multiple organizations.

The good news is that the functions that are underinvested and underemphasized, such as agile, broad analysis, are also less expensive. Achieving balance in the portfolios would not be as economically disruptive as might be thought, especially if some economies can be achieved in big-model work, through consolidation and more efficient data-handling technology.

Subsequent sections discuss how to go about this family-of-tools approach, particularly with respect to use of agent-based models, gaming, and use of experts.

Another crucial issue is replenishing the supply of first-rate analysts. Ultimately, it is the analysts who determine the quality of work done. Even the best M&S will produce little if the analysts are inadequate. This subject, which can be regarded as one of human capital, is beyond the scope of the current study but badly in need of further work (see, e.g., National Research Council, 2006).

## Agents and Other Methods for Improving Model Adaptiveness

### General Approaches

As discussed earlier, M&S must become substantially more adaptive if they are to be able to inform the choice of strategies that are intended to be flexible, adaptive, and robust. The adaptiveness may relate to having (1) submodels that represent decisionmaking by commanders; (2) submodels that adjust simulated strategy and tactics depending on objectives, situation, and projections; or (3) submodels that represent, e.g., the behavior of individuals (perhaps adversary leaders), groups (for instance, a particular regional tribe or the military establishment of a dictator in a losing war), or countries (e.g., a country that might or might not become more nationalistic and resistant as the result of strategic bombing). These are only some of many examples.<sup>25</sup>

The methods available for improving adaptiveness include using agents, control theory, game-theoretic methods, or more ordinary model-related operations-research algorithms. The methods may be deterministic, stochastic, or a hybrid of the two. These methods should be seen as “in competition.” Unfortunately, the book has not yet been written on when each type of method is suitable nor has there been one written on how the methods can be related to each other.

### Agent-Based Models

Rooted in artificial intelligence research, agent-based modeling has been adopted by the complexity sciences because it shows so much promise for dealing with certain kinds of issues, whether they be tactical or in the domain of social-cultural-military interactions.<sup>26</sup> Many types of agent-based models already exist, and other types are needed to fill particular gaps.

One distinguishing characteristic relates to whether the agents are conceived top-down, as part of command and control, or bottom-up, as part of atomic entities that act independently but generate higher-level emergent behaviors (e.g., riots arising from the action of individuals in a crowd, groupings of tribes into coalitions, or steady-state mass behaviors of traffic flow). A second characteristic is whether the agents are part of a simple or sophisticated larger simulation. A third characteristic is whether the agents' internal structures are simple (“light”) or sophisticated (“heavy”). Traditionally, light structures are associated with bottom-up agents populating simple simulations, whereas heavy structures are associated with top-down agents interacting in a sophisticated simulation or using multiple factors and correspondingly multifaceted logic to make decisions or determine other behaviors. In this instance, these types of agents are distinguished by the degrees of competence they must exhibit when interacting in their simulated environments. Further, top-down agents are also often used in “long-life” situations, in which a particular agent needs to behave appropriately and maintain awareness of its environment for a long period of time (hours to days) while performing many different activities during the span of its existence. As the agent-related disciplines mature and expand, hybrids are being developed and all of these distinctions may become less clear.<sup>27</sup>

Many other characterizations of agents exist. Some relevant to the defense-planning analysis community relate to the degree to which agents (1) are autonomous, (2) are “social” (interacting with each other), (3) are purposeful rather than reactive, (4) use decision theoretic logic,

(5) are adaptive in the sense of learning, and, where applicable (as in agents acting as decision models), and (6) reason in ways equivalent to humans in key respects.<sup>28</sup>

The principal observation here is that generalizations are dangerous in a domain as rich and with as much potential as agent-based modeling. Further, despite active and fruitful research over the past decade or so, the field is still young on the time scale of scientific developments. Nonetheless, many applications have already been made and a wide variety of tools already exist.<sup>29</sup>

This said, the question for this paper is how agents can be used in analysis, now or in the future. Experience with agents consistently yields the set of problems seen in Table 4.2.

As the communities cross-fertilize, some of these problems may be mitigated naturally. For example, some work<sup>30</sup> done in top-down agent modeling to facilitate explanation could, theoretically, be applied to bottom-up agents. Cross-fertilization itself, however, is difficult because of disparities in terminology and assumptions among the communities and because researchers often do not work very hard to bridge the gaps. The way ahead for agent-based models is suggested in Table 4.3. Here as elsewhere, we see synthesis efforts as being especially suitable for DoD-level funding (e.g., from the Defense Modeling and Simulation Office—now called the Modeling and Simulation Coordination Office [M&S CO]).

## Using Gaming in Analysis

A natural question is whether human gaming can in practice be used to inform analysis. The stereotype is that human games are idiosyncratic to players, focused on the playing through a single, undocumented, and relatively unstructured scenario.

**Table 4.2**  
**Challenges with Agent-Based Models for Analysis**

<b>Bottom-up Agents</b>	<p>They are not easily generalized. Agents are often built bottom-up for specific contexts, with important knowledge deeply buried and inappropriate for other contexts.</p> <p>Cause-effect relationships of observed behavior are difficult to identify because they result from many micro-level relationships and events.</p> <p>Similarly, explanation capabilities are often quite poor, with the ABM used more as a black-box generator of possible behaviors than as a traditional model.</p> <p>Validation is difficult and unstable because of the many underlying rules and their interactions, which may change across problem areas. Also, the face-validity approach to validation can fail because observed behaviors may not be intuitive (and may not even be valid).</p>
<b>Top-down Agents</b>	<p>Knowledge acquisition and engineering are resource intensive, but shortcuts may result in “brittleness.”</p> <p>Few architectures enable robust, real-time modeling of human decisionmaking; those that do are largely community-specific and require years of expertise to master.</p> <p>Validation becomes more difficult and more resource intensive as the robustness and variability of the models increase.</p>

**Table 4.3**  
**Action Items for Analytical Use of Agent-Based Models**

<b>Science and Technology</b>	
Invest with portfolio approach	Invest in different approaches (e.g., top down, bottom up, hybrid), in abstraction methods for representing ABM behaviors in more analytical models, and in related tools (e.g., knowledge acquisition and explanation)
Write the book	Support DoD-oriented review papers and books relating each method to various problems and functions
Validate	Define and promulgate new concepts of “validation,” such as “validation for the purposes of exploration”
Practice	Develop “code” of best practices for use of ABMs
<b>Applications</b>	
Invest in diverse types of applications	Recognize virtues of applications for discovery, hypothesis generation, rigorous analysis, and the like
Invest in simulation-creation tools	These are needed for rapid development and adaptation of the relatively small, specialty models
Enrich classic force-on-force models	Add decision models to provide adaptivity, probably using top-down agents
Enrich treatment of command and control in M&S	Use ABMs to enable representing core phenomena, such as shared awareness and self-synchronization
Supplement combat-phase models with models of, e.g., stabilization and reconstruction	Use bottom-up ABMs or possible abstractions for modeling of phases in which emergent behaviors are particularly important
Broaden participation and sources	Ensure participation of, e.g., Departments of State and Commerce, or of related experts
Encourage competition and openness	Invest in both open and classified applications, encouraging openness and peer review

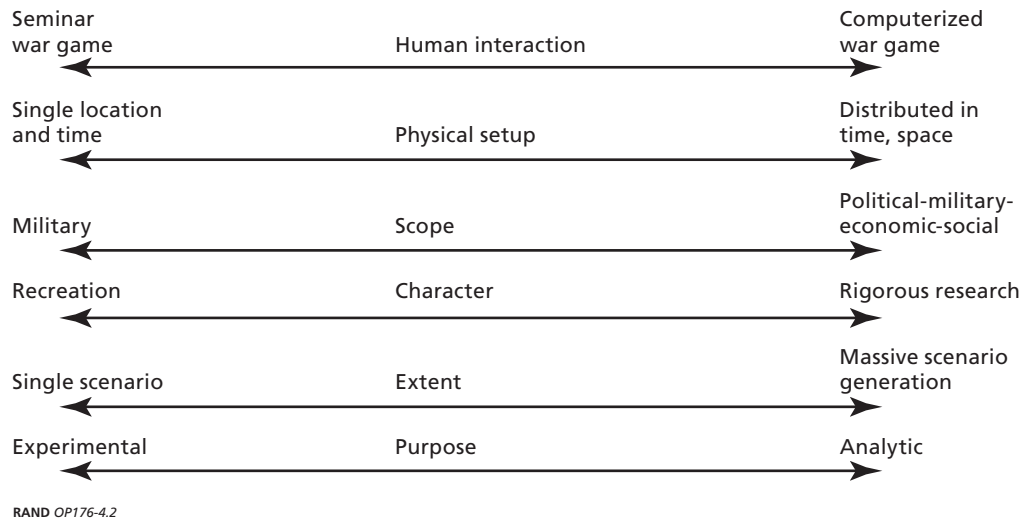
### The Range of “Gaming”

In fact, “gaming” refers to a broad range of very different kinds of activities, so generalizations are unwise. In some cases, gaming is related to mathematical game theory, which seeks to find optimal strategies for the protagonists.<sup>31</sup> In most cases, however, the gaming refers to diverse types of competitive human play undertaken without explicit regard for game theory *per se*.

Figure 4.2 indicates five of the many other dimensions along which types of gaming can be distinguished. In today’s world, most gaming is actually recreational, much of it continuously online with very large numbers of participants. Recreational games differ in character, with some being “strategy” games, some first-person shooter games, and still others that might be called “planning games” (e.g., SimCity).

For the purposes of this paper, we are most interested in games that might be conducted for the Department of Defense as part of modeling, simulation, and analysis (MS&A). Human gaming can be used for at least the following analytical purposes: (1) discovery, (2) sensitization to issues, (3) concept development, (4) knowledge elicitation (e.g., of key factors), (5) identification of assumptions, and (6) testing of hypotheses and strategies.

**Figure 4.2**  
**Spectra Distinguishing Among Characteristics of “Games”**



Examples of such uses of gaming are many if one merely looks. Armies have long used war gaming to test hypotheses and strategies, and sometimes to discover new ones. James Dunnigan and others drew heavily upon study of military history to create recreational war games that were used by young officers well before today’s era, in which analogues are computerized (Dunnigan, 2003). Even though systems analysis is typically associated with “hard analysis,” its pioneers used war gaming extensively,<sup>32</sup> and such games, although much less prevalent, remain important in RAND’s modern-day systems analysis and policy analysis.<sup>33</sup> Aspects of the JICM model (e.g., soft factors and a network rather than a pistons approach) were motivated by the strengths of human gaming (Allen and Wilson, 1987). RAND’s “The Day After . . .” games (Molander et al., 1998) have been used for 20 years for initial cuts at serious policy problems, such as future nuclear weapons use and cyberwar. The U.S. Joint Forces Command routinely uses a model-game-model approach. And, quite recently, OSD (PA&E) has used gaming to study issues in the resourcing for and employment of special operations forces. In the academic realm, a new discipline called “serious games” (to distinguish it from recreational games) has been emerging. Serious games are defined as mental contests, played on a computer according to certain rules, that use entertainment to further government or corporate training, education, health, public policy, and strategic communication objectives (National Research Council, 2006).<sup>34</sup>

These examples constitute existence proofs of analytical applications, but much more can in fact be done. The following subsections describe three possible approaches.

### Using Human War Gaming Analytically

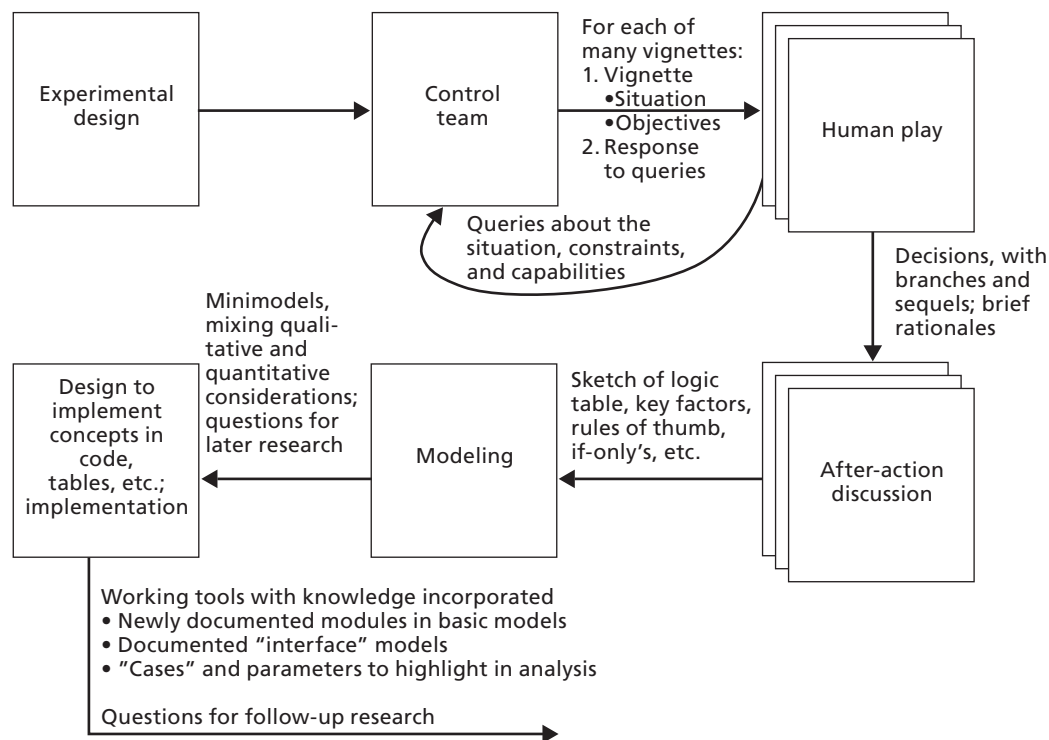
How to make human war gaming more “analytic” deserves an entire paper; however, one approach can be summarized as follows (see also Figure 4.3):<sup>35</sup>

- Design the games as vignettes, with relatively well-described situations.

- Use competing teams with different backgrounds (e.g., from the United States, the UK, Israel, and Poland) to see diverse tactics and assumptions.
- Encourage teams to develop explicitly contingent plans (e.g., with branches and sequels).
- Protect the teams organizationally, perhaps by embedding them in independent groups such as federally funded research and development centers, war colleges, or U.S. Joint Forces Command.
- Record planning factors and reasoning used during team play, recognizing them as the germs of “models” that can later be formalized, whether quantitatively or qualitatively.
- Use red teams, both to better appreciate different ways of assessing the situation and defining objectives and to draw upon expertise about adversary military doctrine.<sup>36</sup>
- Follow up with analysis and modeling.

Analysis should come both at the beginning and at the end of the diagram shown in Figure 4.3. People skilled in capabilities analysis should design the war games and vignettes to cover the space adequately (perhaps with a combination of experimental design and M&S greatly narrowing the number of cases). Analytically inclined people with an appreciation of and openness toward soft factors should record intra-game logic and then develop summary qualitative models. Subsequently, modelers should relate the variables of the human games to variables of models and simulations.

**Figure 4.3**  
**A Process for Using Human War Gaming Analytically**



What is perhaps remarkable here is that such an agenda appears plausible. It does not require any breakthroughs in science or technology. It merely posits that good traditional quantitative analysts bring their skills to bear on a problem that has often been studied in the past by historians, political scientists, and military officers without much formal analytical training.<sup>37</sup>

### **Using Gaming to Help Inform Building of Adversary Models**

A different approach is to use gaming to inform and tune adversary models, starting from a theoretical structure. In this approach, gaming is used to test an initial model and suggest additional variables. Procedurally, the following is the approach:<sup>38</sup>

- Develop a theory and structure for understanding possible high-level adversary decisions and behaviors.
- Use political-military seminar war gaming to check on the adequacy of the factors and structure, and to test the theory in particularly difficult or ambiguous situations.
- Iterate the theory and use it to generate alternative adversary models, each of which is parameterized to reflect inherent uncertainties, even for specified conditions.
- Use these adversary models with exploratory analysis to develop or test candidate flexible, adaptive, and robust strategies.

Precedents for this exist at several levels of detail. The same methods can also be used to build models of U.S. or third-party decisionmaking, or models for counterterrorism (Davis, 2006).

### **Optionally Interactive Simulation in Building War Plans**

A third approach is optionally interactive simulation, where humans may be used to make command and control decisions, such as shifts in strategy or commitment of reserves. At one time, this was actually necessary, but as M&S improved, the aspiration was to eliminate human play so as to improve reproducibility and perceived rigor. In some systems, interactivity was explicitly proscribed (as with the original JWARS); in others, it was permitted at some natural points (so-called interruptible simulations) but seldom emphasized. The tack suggested here is as follows:

- Have humans sketch out the “war plans” to be used in simulations.
- Represent the war plans in the simulation.
- Conduct the simulation with interruption points at which humans review the situation and, as necessary, make adjustments in the strategy with new building-block actions.
- Add the new action sets or triggering rules to the simulation.
- Iterate until automated play represents well the strategy and adaptations of the humans.
- Repeat this process with different human teams, so as to develop a set of alternative strategies and building-block actions, for both red and blue (to use the old bipolar structure) and, as necessary, for third parties.



This mode of operations has some associated technical requirements. First, interruptible play must be possible. Second, strategies must be conveniently representable, to include branches and sequels triggered by state-dependent rules. Third, it must be possible to construct easily accessed libraries of building-block actions, a number of which might be used in any given strategy, perhaps conditionally. In past work, this style of man-machine operations has been found to be quite effective.<sup>39</sup> It appears not to have been much used in recent years, however.<sup>40</sup> That should change.

Variations and combinations of this approach exist at “entity level,” as in building adversary models using an interactive approach in a commercial game environment (Henninger et al., 2003). Similar methods could be used for defense-planning simulations.

Table 4.4 summarizes way-ahead information for better use of gaming to inform and supplement M&S-based analysis.

### Making Better Use of Experts in M&S

Another aspect of a family-of-tools approach is making better and more systematic use of experts. There is no dearth of methods for using experts. Some of the many methods include Delphi (Helmer-Hirschberg, 1967; Linstone and Turoff, 2002), the Analytic Hierarchy Process (Saaty, 1999), Value-Focused Thinking (Parnell, 2004), Subjective Transfer Function techniques (Veit, Callero, and Rose, 1984), Scenario-Based Planning (Schwartz, 1995), “Day After” games (Mussington, 2003), Policy Analysis Market (Looney, Schrady, and R. Brown, 2001), Uncertainty Sensitive Planning (Davis, 2003a), and Assumption-Based Planning (Dewar, 2003). A new method that envisions mixing exploratory analysis with use of experts is called Massive Scenario Generation (Davis, Bankes, and Egner, forthcoming).

**Table 4.4**  
**Action Items for Improving Use of Gaming in Support of MS&A**

Science and Technology	
Write the book	Develop primer on how the various types of gaming can be used for the various types of analytic activities, ranging from discovery to rigorous evaluation
Specific issues	Develop and test methods for at least the following: (1) using human war gaming analytically, (2) using seminar gaming to inform and evaluate adversary models, (3) using humans in optionally interruptible simulations to help develop and hone adaptive strategies and related libraries of building-block actions that can then be used in closed simulation
Technology	Evolve technologies in support of 1–3 above (no breakthroughs are necessary)
Within Analytic Studies	
Specific studies	Include in terms of references for major DoD analytic studies in which gaming will be used, including red teaming and gaming with diverse participants (e.g., Israeli or British officers, cultural anthropologists, and experts with backgrounds in on-the-ground diplomatic and economic work)

Nor is there a shortage of “platforms” in which to place expert knowledge to use in models. Examples include agents, influence nets, rules and submodels in system dynamics, the plans represented in simulations, and so on.

Typical experience attempting to elicit expert knowledge has been less than satisfactory, however. Some of the principal difficulties have been

- challenges in finding the experts in the first place (if they even exist and are available easily for DoD work)
- the need to recognize and deal with the fact that experts often have “agendas”
- unfortunate group dynamics, such as effects of hierarchy and social context and the well-known “group think” phenomenon
- inappropriate selection, as in merely inviting the “usual suspects,” or, worse, inviting only those expected to support a concept being evaluated
- difficult cross-disciplinary discussions due to experts from diverse disciplines having different languages, assumptions, and tacit knowledge
- the insidious tendency for the organizers of expert discussion, and perhaps the group of experts itself, to move toward a best estimate or consensus, rather than distributions of possibilities or exploiting the so-called wisdom of crowds
- human shortcomings in thinking through the implications of complexity, which includes nonlinearity, multiple types of feedback, concurrent interactions (National Research Council, 1998, p. 15)
- shortcomings of experts in verbalizing their reasoning or even in recognizing that a cognitive process has occurred (Deutsch, 1993).

Doing better is not necessarily straightforward, and contrasting paradigms exist on how to use experts, as summarized in the following dichotomies:

- the wisdom of crowds versus finding the top expert
- blink versus think
- rational-analytic versus naturalistic
- multidisciplinary versus interdisciplinary
- collaboration versus independent activities
- reasonably like-minded versus creative tension.

The conflicts are sometimes more apparent than real, with different methods being suitable in different circumstances. Nonetheless, the list suggests the need to think about the issues seriously.

The way ahead in this area should include the actions suggested in Table 4.5.

**Table 4.5**  
**Action Items for Improving Use of Experts in Support of MS&A**

<b>Science and Technology</b>	
Write the book	Develop primer on how the various techniques for using experts apply in DoD work. Spin off learning materials for continuing professional education for military officers and DoD civilians
Specific issues	Find or develop better techniques for abstracting expert assessments from groups, without omitting significant outliers <sup>a</sup> or seeking consensus, but while nonetheless eliminating counterproductive “noise”
Technology	Review technology available to best-use consultants for DoD MS&A purposes, colocated or distributed
<b>Within Analytic Studies</b>	
Specific studies	Specify in terms of references for major DoD analytic studies that experts will be used and, where appropriate, specify the kinds of expert advice being sought (e.g., specify the use of independent red teams and mechanisms to ensure that their concerns are both captured and assessed)

<sup>a</sup> Related matters are discussed, for example, in the literature on risk, as in discussion of distributions with “thick tails” (Haimes, 1998).



## A New Business Model

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### Background: A Closed Analytical Culture and Related M&S

#### The Analytical Culture

A decade ago, DoD's analytical culture was characterized negatively by a Defense Science Board study as in Table 5.1. This description emerged as a consensus from a lengthy and passionate panel discussion. Although some of the concerns are no longer as valid as they once were, others continue to be. Indeed, very similar concerns were raised in 2006 by participants in a workshop (see Appendix B) contributing to this paper and featuring people with recent industry experience. The principal point is that DoD's analytic culture tends to be "closed," with an emphasis on "authoritative" models and data and on bureaucratic consensus building. Such an organizational culture tends to far less agile, far less dynamic, and far less sensitive to uncertainty than one that is more open, competitive, and freewheeling. The recreational-gaming industry is a good example of the latter.

**Table 5.1**  
**Changes Needed in DoD Analysis Culture, as Seen in 1996**

What Is	What Should Be
Closed	Open
Bureaucratic review	Peer review
"Accredited" analysis	Competitive analysis
Model orientation	Subject orientation
Mechanical	Meaningful
Data poor	Data rich
Rigid approvals	Learning and adaptation
Stable algorithms	Unstable phenomena
Suppression of uncertainty	Illumination of uncertainty
Suppression of risk	Illumination of risk
Narrow Cold War style	Oriented to now and future
Few accredited scenarios	Many political-military scenarios
Point assumptions	Exploratory analysis

SOURCE: Adapted slightly from Defense Science Board (1996).

There are advantages and disadvantages to each of the styles, but the nature of military developments and the explicit demands of policymakers on the analytic community strongly suggest the need for a strong dose of the features in the right column of Table 5.1.

### **M&S Technology and Relationship to Culture**

Contributing to the analytical culture is the nature of DoD's very approach to M&S, i.e., its implicit business model. The history of DoD M&S in support of higher-level analysis, such as force planning, has revolved around monolithic models. Such models were designed to be used as a whole. To be sure, even early models were designed with a clear concept of parts, such as air-to-air, ground, and naval combat (Hughes, 1989), and programmers intimately familiar with the models can turn portions on or off, or make changes to parts without too much effort. However, "mere mortals" often cannot. Furthermore, the big models have been developed with relatively low-level computer languages making it impossible for typical analysts to make quick changes themselves. The results are big models and analytical processes that have been slow to change.

### **Improving Agility (and Quality) with Modern Technology**

Before proceeding, we note that there are advantages to monolithic designs and low-level programming languages. They can be efficient, and the pieces have been designed and mutually tuned to work well together, at least for the domain of cases anticipated by their designers. They are "integrated" in the old sense in which that term was once used, and much good work can be done with them. Nonetheless, modern theory and practice for design and development of both software and models emphasize modularity,<sup>41</sup> by which we mean strict technical modularity. Individual modules are developed and tested separately. Various combinations are then assembled as needed, interacting only through well-defined interfaces. The ability to do this is often called composability or component-based design.<sup>42</sup> Object-oriented modeling is one example with a substantial record of success over the past decade or so.<sup>43</sup>

The advantages to such modularity are immense and affect quality, testing, comprehensibility, and maintainability. From the viewpoint of this analysis-centric paper, some of the principal advantages are these:

- *Flexibility and adaptiveness.* A new module can be specialized for a particular problem and swapped in. Modules of different resolution can be prepared (and even included in the program) so that, at run time, analysts can choose.
- *Continuous improvement.* Modular approaches enable continuous improvement as more knowledge becomes available. Making changes does not require exquisite knowledge of the overall M&S in which the module appears.
- *Cooperation.* Cooperation can be achieved across organizations, with different groups addressing different modules or different approaches to the same module. Some modules may be reused.

- *Competition.* For similar reasons, competitions can be held comparing alternative designs, with either the “best of breed” emerging or with alternative versions coexisting for specialty purposes.

The above items relate to modularizing a “big” model. However, true modules are also models in themselves; they can be used separately, without the complications and overhead of the entire system. Furthermore, the modules can be reprogrammed in higher-level languages (e.g., Visual Basic, Excel, or Analytica), creating stand-alone specialty models that are very accessible to analysts and also changeable by those same analysts.

Since so many current problems of defense planning relate less to sizing total joint forces for simultaneous big wars than to making good choices about options within various joint capability areas or investment choices across capability areas, analysis may often be best accomplished with specialty models and combinations thereof, rather than by using the big simulations.

Opinions and tastes differ on this matter, but increasing the relative emphasis on such specialty models would likely clarify and sharpen the key analytical issues. Ideally, these should have very clear relationships to modules of the “big” models so that comparisons of competing analyses would remain straightforward.<sup>44</sup>

What does a “clear relationship” mean? It might be convenient to use modules of a big simulation as stand-alone models (e.g., of strategic mobility or close-range ground combat). Doing so requires a separate input-output interface, but the algorithms and data structures are identical to those of the relevant module in the larger simulation. Had the big simulation been built with this in mind, the user could instead use just those parts of the big simulation as are needed and work from a simplified interface consistent with the more comprehensive one.

Suppose, however, that the analyst does not want to be bothered with the complexity of understanding the big model or how to use it like a maestro. Suppose that he wants to do some of the model runs himself and have complete control and understanding, but of a relatively narrow problem, such as how best to achieve a particular capability, for example, air-to-ground interdiction or persistent surveillance over ground forces. Such an analyst might prefer a specialty model, perhaps built with Microsoft Excel or Analytica (used extensively by both RAND and MITRE in higher-level studies). The relevant algorithms and data structures might be entirely consistent with those of the big model; might be somewhat different, but in ways not fully understood; or might be *optionally* different in known and precisely described ways. Ideally, the latter circumstance would apply, but that does not come about naturally, because analysts are typically more concerned about their studies than keeping track of precisely how their tools relate to other tools. To reinforce the point, it is often the case that the analysts using specialty models are able to do very insightful and compelling analysis quickly, without the overhead of a big model that does not even include some of the considerations the analyst feels are important (they could be added, but only by negotiating with the model’s developers, keepers, and perhaps some configuration-control board).

We have, then, a classic conflict. On one side are those who emphasize standardization using authoritative models and databases and configuration control. They know that such things are very important in joint work, so that all participants in the analytic wars are on the

same playing field, and in which it should be difficult for losers to obfuscate results by attacking the model or data. On the other side, we have those who wish to be agile, unencumbered by big-model overhead, problem focused, and unburdened by what they see as excessive concern for consensus and excessive devotion to standard but unreliable data and assumptions, many of which obscure important uncertainties. Some individuals work both sides of the divide, from time to time, but most do not.

Our recommendation is to improve the openness, dynamism, quality, and agility of DoD's analysis by applying related practices to M&S:

- Improve the modularity and “composability” of the department's key big models, so that they can be improved and adapt more rapidly and benefit from the marketplace of ideas.<sup>45</sup>
- Explicitly increase investment in smaller, specialized models supporting agile analysis, and in the tools and techniques for developing them rapidly.<sup>46</sup>

Interestingly, both of these could be accomplished simultaneously, to the extent that the big-model modules are viewed in parallel with the separate models. That is, someone with a good specialized model should be able to reprogram it so that it can be a replacement module of the large model. And, conversely, a good large-model module can spin off a self-contained specialized model (or, perhaps, be used within the big-model structure by turning off and hiding unused modules). It should certainly be possible to develop routine procedures for comparing assumptions and results of alternative models. Thus, our third admonition is

- As a somewhat lesser priority, invest in developing easy and well-oiled procedures for comparing alternative models and their results—not so as to achieve equivalence, but so as to understand differences (and be able to achieve equivalence in well-defined limits).

Given the concerns of policymakers about the inadequacy of current M&S for the new challenges, the highest priority should be on the first two items above.

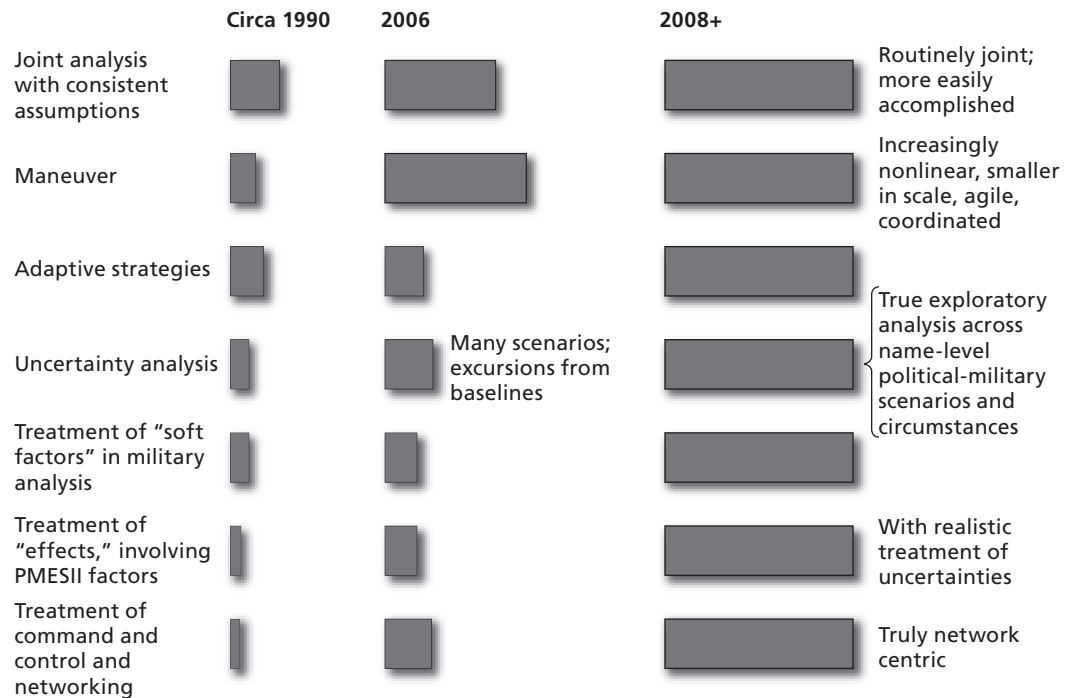


## Conclusions and Investment Recommendations

### The Evolution of Analysis M&S

Policymakers have identified new challenges for analysis in support of defense planning, which in turn has generated new requirements for M&S. As the way ahead is pondered, it is useful as well to note where we have been, where we are now, and where we want to be. Figure 6.1 provides such a picture. Although only notional and schematic, with no firm basis in empirical work, the picture conveyed is thought to be accurate.

**Figure 6.1**  
Progress and Prospects



NOTE: Bar lengths are schematic indications of quantity and quality.

RAND OP176-T-6.1

The first point is that M&S support for defense analysis has improved substantially over the past 15 years. Comparing the situation today with that in 1990, we see far more jointness, carefully integrated studies with substantial richness, and a common baseline of standard scenarios and assumptions on the basis of which to do analysis of alternatives.<sup>47</sup> Today's analysis is quite good at representing higher-level maneuver of large forces. We also see improvements in treating uncertainty, "soft factors," the concept of "effects," and command and control. As the figure suggests, however, much more should be demanded over the years ahead, much of it in the near to mid term, since no technological breakthroughs are necessary.

Jointness and common baselines should improve further and, importantly, be achieved with far greater efficiency. Representation of maneuver will need to be better for the increasingly nonlinear battlefield and for the world in which important maneuvers occur with smaller, more agile, highly coordinated forces, sometimes deep into enemy territory, and often in the context of highly irregular combat.

Particularly relevant to the new challenges, however, tomorrow's M&S must include highly adaptive strategies because they will be used to evaluate alternative flexible, adaptive, and robust (FAR) strategies. Such evaluation will require testing across a broad possibility space and M&S that represent the planned and unplanned adaptations possible under the different strategies. This implies a far more extensive approach to uncertainty analysis, one characterized by true exploratory analysis not only across diverse name-level scenarios (e.g., crisis with Iran), but within each such scenario. Treatment of soft factors should be routine and related sensibly to underlying factors. Treatment of effects should not only be routine and extensive, but should also provide sound information on the range and rough distribution of possible effects—including those that are counterproductive or better than anticipated. Future M&S should, where needed, be exceptionally good at representing network-centric planning and operations.

## Summary Recommendations on Investment

Many of the recommendations and suggestions above relate more to emphasis and management than to DoD-level investment. Table 6.1 instead focuses exclusively on DoD-level investments. These are seen as common goods particularly worthy of DoD-level attention, whereas the vast bulk of M&S work—even that relevant to DoD analysis—is and should be conducted by the various services and defense agencies. Table 6.1's recommendations fall into three categories, consistent with the DoD priorities discussed earlier. Within each category, the table indicates desirable policy actions—essentially the "spin" to be applied in expressing requirements and writing terms of reference; investments and their priority (1, 2, or 3) within the category; and suggestions as to whom the sponsor might be and the amount of investment that might be needed.

Note that *all* categories have the same overall priority. Categories 2 and 3 relate specifically to many of the "new" DoD leadership demands and priorities, but category 1 relates broadly to the core, continuing DoD work in planning its programs and balancing its associated portfolios of investments.

**Table 6.1**  
**Summary Recommendations for DoD-Level Investment**

Action Class	Policy Action		Investment	Sponsor/Rough Cost Estimate
Routine treatment of uncertainty, including deep uncertainty	Analysis should emphasize evaluation of alternative strategies for potential flexibility, adaptiveness, and robustness	1	Increase openness, competition, agility, and capability, including for broad, low-resolution exploratory analysis, by (1) integrating and improving existing models to achieve a single, integrated, and very modular multiresolution campaign model; and (2) spinning off or developing separately small, specialized, and readily modified models. Establish cross-calibration with service models. This constitutes a new “business model”	PA&E/\$3–\$4M over two years, but with a net savings over time
		1	Generalize and expand current exploratory analysis methods and tools for portfolio work so that related choices can be robust to uncertainty about underlying assumptions about scenarios, category weights, risks, costs, etc.	M&S CO, AT&L, PA&E/\$1M over two years initially. Later, \$2M for creating products
Routine treatment of complex human and social issues (all PMESII dimensions)	Require study components such as gaming, red teaming, use of experts, and use of model families representing all PMESII dimensions	1	Develop consolidated primer on use of gaming, red teaming, and use of experts for higher-level DoD analysis, and for connecting results to M&S. This should include in-depth discussion	M&S CO/\$1M–\$2M for a cooperative effort of two organizations over two years
		3	Commission report drawing upon community knowledge to recommend new VV&A guidelines focused more on exploration than prediction	M&S CO/\$250K
Adaptiveness of M&S for PMESII issues and network environment	Require that models permit optional human play or insertion of results of PMESII-rich games	1	Develop review paper covering adaptive modeling methods relevant to higher-level DoD work. This should cover agent-based models, control theory, game theoretic, and other operations research methods	M&S CO/\$500K
		2	Experiments on PMESII-sensitive model-and-game families, aspiring to well-established relationships among low-, middle-, and high-resolution models	M&S CO/\$1M–\$2M over two years, covering at least two efforts
		2	Develop primer on effective use of human-in-the-loop analysis with simulations of varied resolution and character	M&S CO/\$1M–\$2M for a cooperative effort of two organizations over two years
	2	Require serious treatment of future network-centric capabilities and implications	Commission competitive design for new or substantially reprogrammed campaign and mission-level models built around network centrality (and degrees thereof). Priority 2 only because of high cost	Joint Staff/\$2M for industry competition and review. \$5M–\$40M eventual cost, assuming reuse

NOTE: The number column indicates the relative priorities within each category.

Some words are appropriate regarding the estimates of cost. It would be very easy to expand ambitions and stimulate large, expensive software-development activities—not on the scale of JSIMS and JWARS, but on the scale of tens of millions of dollars. That is not what we suggest. Instead, the recommendations focus on a combination of (1) consolidation activities, (2) work on critical enablers, (3) “sense-making” research to make sense out of what often seems chaotic and unplanned, (4) common-good systematic research, and (4) fresh design work.

To put it differently, Table 6.1 omits many high-priority investment items, e.g., advanced agent methods to assist in modeling and analysis of culture-sensitive issues, only because they are *apparently* being pursued by the services, commands, and defense agencies. OSD should ensure that this is true and, if it is not, arrange for changed priorities. We mention this because, although a good deal of related research has been funded in recent years, quality and results have been predictably varied. A worry is that funding organizations would back away from the new and difficult subjects requiring fundamental rethinking and experimentation. Instead, continued investment is badly needed, although more coherence and emphasis of synthesis should also be sought. Much of the work needed is in the province of science and technology and, thus, the province of the Director for Defense Research and Engineering.

Within the first action class of Table 6.1 (routine treatment of uncertainty), the first recommendation is complex, calling for improvement of big models *and* support of simpler models (often specialty models) *and* assuring the ability to compare the models. This recommendation requires special discussion because, taken as a whole, it corresponds to a distinctly new business model for DoD-level investment. As a whole, the need exists for greater openness, competition, agility, and capabilities. Past investments have tended to emphasize standardization, and the predictable result has been to generate models and modeling activities that are good at what they do, with consistent data, but that lack the vigor, creativity, and cross-cutting flexibility that are needed. DoD should, on the one hand, integrate and improve its current strategic models, make the result as modular as possible, and actively plan continuing competition and evolution at the module level. Different module versions will likely be superior in different analyses, whether because of resolution or which phenomena need to be represented well. Some module versions might allow for optional human play or might be tuned to recent empirical information. DoD should, on the other hand, also encourage and use more relatively small specialty models, whether for agile aggregate-level work or for very narrow analysis of mission capabilities—analysis unencumbered by the weight of full campaign models. DoD should also invest modestly to ensure that researchers are able readily to compare assumptions and results of, e.g., the specialty models and relevant big-model modules. In some cases, a specialty model may be identical, except for programming language, to a big-model module; in other cases, there may be important and desirable, but optional, differences. Similarly, cross-comparison mechanisms should exist to ensure that DoD’s integrated campaign model has understood relationships with relevant service-level models.

This recommendation is complex, but we urge honoring its complexity rather than investing only, for example, in the consolidation and integration of current strategic models for the sake of greater efficiency and standardization.

The second recommendation in this action class is to generalize the concepts of “exploratory analysis” for effective application in portfolio analysis, e.g., analysis to inform resource allocation within a capability area or across multiple capability areas. The allure of portfolio methods is considerable, but the results are often bogus because the results depend too sensitively on a myriad of low-level assumptions. As with capabilities analysis generally, the solution is to seek flexible, adaptive, and robust strategies of investment, which requires exploratory analysis in which the assumptions affecting the resource-allocation decisions are systematically varied.

Within the second action class (routine treatment of complex human and social issues), our primary recommendation is for DoD to develop an integrative primer on the use of methods, such as red teaming, war gaming, and use of experts. This is a class of issues that is ripe for coherent and meaningful synthesis, which is not an effort for a committee. We also mention the need to revise policies on verification, validation, and accreditation (VV&A) so that they acknowledge and deal sensibly with the vast array of models (and associated data) that is simply not “predictive” in the classic sense, but rather are intended for more exploratory work amid uncertainty.

Within the third action class (adaptiveness and networking), we again recommend a synthetic activity, starting with one that pulls together methods such as agent-based modeling, control theory, and game theory so as to clarify which methods for providing adaptiveness are most suitable. We also recommend recognizing that a new generation of strategic/operational-level model is needed for the network-centric era. Even JWARS (now JAS) has only some of the features needed, and we do not believe that any consensus yet exists about what a new-generation model might look like. This suggests the need for preliminary research and a competition of ideas. This is distinct from and in addition to network-centric models necessary for design and evaluation of particular systems of systems, which are of great importance within the acquisition community.



## “Analysis Practices Working Group,” March 14–16, 2006

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A workshop was held at the Institute for Defense Analyses, March 14–16, 2006, organized by the Institute for Defense Analyses (IDA) and representatives from RAND and MITRE. One of the working groups (Working Group 3), which we chaired, focused on analysis practices.<sup>48</sup> Attendance was by invitation only, with group members nominated by their respective organizations. Nineteen people (Table A.1) participated throughout; some additional participants were able to sit in during portions of the proceeding.

An important aspect of the working group’s effort was to take an unrelenting analysis-centric view, rather than being concerned too early and exclusively with particular modeling and simulation issues. Two expert panels provided brief, but very candid and useful, suggestions from the perspective of analysis organizations to which modeling and simulation are merely tools along the way. These suggestions, then, presented a view of “demand,” above and beyond the useful material in the 2006 Quadrennial Defense Review and other formal documents. In addition, a few individuals were asked to give short presentations on specific topics of interest: U.S. JFCOM’s recent experience with a combination of modeling and war gaming,

**Table A.1**  
**Members of Analysis Practices Working Group Panel**

Paul K. Davis, Chair (RAND)	Andy Kourkoutis (J-8)
Amy Henninger, Cochair (IDA)	Mary McDonald (N-81)
Sheila Bankes (Calculated Insight)	Jimmie McEver (EBR)
Chris Chartier (NII)	John Robertson (CAA)
Ed Crowder (A-9)	Vince Roske (IDA)
Augie Fucci (DAMO CI)	Scott Schutzmeister (AMSO)
Jeff Hamman (JHU APL)	Stuart Starr (Consultant)
Eric Johnson (JDS)	Bill Woodson (U.S. Marines)
Rick Kass (JFCOM J-9)	Derk Wybenga (J-4)
Bill Key (TRANSCOM J-5)	

NOTE: See the Abbreviations list for the affiliations.

lessons learned from NATO’s “Code of Best Practices” for command and control analysis, OSD’s use of human gaming to represent the challenges of special operations forces, and new tools for social-cultural modeling, simulation, and database development. Table A.2 lists the presenters.

**Table A.2**  
**Presenters at Working Group 3**

<b>Presenter</b>	<b>Affiliation</b>
<b>DoD Panel</b>	
Eric Coulter	OSD (PA&E)
David Alberts	OSD (NII)
Andrew Hoehn	RAND Corporation (previously OUSDP)
Brigadier General (S) Woodward	J-8
<b>Services Panel</b>	
Jackie Henningsen	Air Force A-9
Robbin Beall	Navy N-81
Mike Bailey	U.S. Marine Corps (MCCDC)
Mike Moore	
<b>Short Briefings and Subjects</b>	
Stuart Starr (NATO Code of Best Practices)	Consultant
Rick Kass (JFCOM Wargames and M&S)	U.S. JFCOM
Mike Ottenberg (Gaming of SOF [Special Operations Forces] Issues)	OSD (PA&E)
Sue Numrich (Modern Tools for Social-Cultural Analysis)	Consultant

NOTES: PA&E: Program Analysis and Evaluation; NII: Networks and Information Integration; OUSDP: Office of the Under Secretary of Defense for Policy [could be abbreviated OSD(P)]; MCCDC: Marine Corps Concept Development Center.



## “Methods Working Group,” June 26–27, 2006

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A workshop was held at the Institute for Defense Analyses, June 26–27, 2006, the purpose of which was to obtain industry responses to the challenges identified in earlier work under the project. There was special interest in augmenting the challenges as necessary and hearing about potential “solutions” in meeting those challenges. The methods working group was by invitation only. Fourteen people participated throughout (Table B.1), of which eight made presentations. Discussion was extensive and, as in the earlier workshop, took an unrelenting analysis-centric view, rather than focusing on particular M&S per se.

**Table B.1**  
**Participants in the “Methods Working Group”**

Panel Members	Presentations
Paul K. Davis, Chair (RAND)	
Amy E. Henninger, Cochair (IDA)	A Case for Using Ensembles in Analyses for Military Decisionmaking
Jason Dechant, Recorder (IDA)	
Gerald Bracken (IDA)	
Mark Altaweel (Argonne National Labs)	Development of Modeling and Simulation Applications in Support of National and Homeland Security
Michael Anderson (Boeing)	Boeing Approaches: Tools and Data Focus Challenges
Steve “Flash” Gordon (GTRI)	
C.R. Krieger (DRC)	Missions and Means Framework Integration and Transition
Dell Lunceford (Total Immersion)	Oh My God, Not Another DoD “M&S–What Should We Do” Workshop
Scott Matthews (Boeing)	Characterizing Uncertainty and Risk (tool)
Jonathan Prescott (Metron)	
James Saultz (Lockheed Martin)	Proprietary presentation
Rich Wicker (SPA)	
Leah Zimmerman (Green Manor Group, LLC)	Cultural Demographics for Better Decisions

NOTES: Company abbreviations: GTRI: Georgia Tech Research Institute; DRC: Dynamics Research Corporation; SPA: Systems Planning and Analysis.



## Illustrative Contrast of Questions for Analysis from the Previous Era and Today

**Table C.1**  
**A Contrast of New and Old Questions for Analysts**

Old Questions	New Questions
<b>Force Structure</b>	
How much force structure do we need for defense of Europe, Korea, and Southwest Asia?	How much force structure do we need, given worldwide interests and commitments, the global war on terrorism, and diverse missions and complex contexts?
Is defense feasible in the Persian Gulf, against regional powers or against the Soviet Union? What kinds of forces and strategy would be needed?	How do we balance investments across missions involving rogues, failed or failing states, regional peers, and the terrorist threat? And across activities such as combat and stabilization?
How should we structure the “total force” with a combination of active, reserve-component, and national-guard forces?	What “total force” should we have for the future, given the range of missions and scenarios, and the now-demonstrated need for and necessity of using national-guard and reserve forces in combat?
What mix of capabilities do we need to cost-effectively achieve the “best-estimated” needs for stopping a large invasion (through attrition of the invading army)?	What building-block capabilities would cost-effectively maximize a future joint commander’s ability to achieve desired effects involving enemy top leaders, leadership levels, rank-and-file military personnel, the population as a whole, and specific populations in particular?
<b>Approach to Military Operations</b>	
How can we assess the concept known as Air-Land Battle?	How do we assess effects-based operations, rapid decisive operations, and information operations? How do we characterize and minimize risk?
How do we fold in NATO-alliance issues as we conduct defense planning relevant to Europe and other regions?	How do we orchestrate all relevant military instruments, and indeed all instruments of national and allied powers, to achieve desired effects at the level of individuals, small groups, and national populations?
<b>Modernization</b>	
What could be accomplished with “stealthy” aircraft that would be essentially undetectable by traditional radars?	Can we build adequately survivable and otherwise capable aircraft for countering maneuver of relatively large ground-force units and mobile missiles far from the shore and far from secure airfields?
Can we count on high-tech precision weapons and how many of them should we buy?	How do we assess networked capabilities? Can we count on their effectiveness? How much redundancy is needed?
What mix of deep-attack precision weapons would be optimal (for specific war scenarios)?	How do we make tradeoffs involving C4ISR, involving networking, systems of systems, information operations, and traditional force capabilities?



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## Endnotes

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This paper is not intended as a literature review, but the following endnotes provide numerous pointers to the relevant literature. We have emphasized citations that are readily available as full papers or books. Many of the papers are available online.

### Summary Endnotes

- <sup>1</sup> MATLAB® is a registered trademark of The MathWorks Inc.
- <sup>2</sup> JWARS: Joint Warfare System; JAS: Joint Analysis System.

### Endnotes

- <sup>1</sup> Separate white papers have been prepared on modeling of traditional warfare (Bracken et al., 2006), non-traditional warfare (Dechant et al., 2006), technology for M&S (Banks et al., 2006), and data issues in M&S (Data Working Group, 2006).
- <sup>2</sup> See also a recent National Academy report (National Research Council, 2006). Some of the material in this paper overlaps with the senior author's contributions to that report. The NRC study also includes a chapter on Education, Training, and Professional Practice, as well as, e.g., more discussion of social modeling, composability, and "serious games."
- <sup>3</sup> Some effects-based operations (EBO) issues have been discussed in the public domain (Deptula, 2001; Davis, 2001; Smith, 2003; Smith, 2006). A web link to many sources is <http://www.saunalahti.fi/fta/EBO.htm> (as of December 18, 2006). Effects-based operations are controversial in some respects (Davis and Kahan, forthcoming; Jobbagy, 2006), particularly with regard to what is and is not new, terminology, whether "predictiveness" is an appropriate goal for effects-based operations analysis, and the processes appropriate for implementing them. The core ideas, however, are sound, and involve worrying about finding actions that will improve the odds of achieving desired PMESII effects, whether direct or indirect, and of avoiding undesirable effects. Doing so often requires a complex "system view."
- <sup>4</sup> Complex adaptive systems research has burgeoned over the past 15 years, and many good sources exist—some popular (Waldrop, 1992), some relatively nontechnical but solidly based in science (Holland and Mimaugh, 1996), some more technical (Bar-Yam, 2003), and some applied to military problems (Ilachinski, 2004; Grisogono, 2006b).
- <sup>5</sup> A number of good references exist on network-centric operations (Cebrowski and Garstka, 1998; Alberts, Garstka, and Stein, 1999; Alberts and Hayes, 2003; National Research Council, 2000), including a recent study on implications for command and control (Alberts and Hayes, 2006).

<sup>6</sup> “Possibility space” spans the areas not only of name-level scenarios (e.g., war with Iran), but also the vast range of circumstances that apply to any one such name-level scenario. This use of “possibility space” is equivalent to the use of “scenario space” in other publications (Davis, 2002a).

<sup>7</sup> The theme of adaptiveness has been emphasized for some years (Davis, 1994) and helped motivate the move to capabilities-based planning (Davis, 2002a), but it is only now becoming mainstream. Its core role is also emphasized in recent work by researchers in Australia’s Defense Science and Technology Organization (Grisogono, 2006a and b), drawing heavily on lessons from natural complex adaptive systems.

<sup>8</sup> This understates the point. Traditional analysis is often considered by such planners as being irrelevant because it omits so many key factors, including human action.

<sup>9</sup> See Gordon and Trainor (2006) and Franks and McConnell (2004).

<sup>10</sup> Although the literature on real-options theory is now quite extensive, including recent books (Mun, 2005; Copeland and Antikarov, 2003), we benefited particularly from a workshop presentation by Scott Matthews, including his discussion of actual use at Boeing in recent years, based significantly on a simplified mathematics that makes the theory more practically accessible (Datar and Matthews, 2004). Interestingly, some aspects of Boeing’s approach relate closely to what we have referred to in this paper as exploratory analysis under uncertainty, multiresolution modeling, and family of tools.

<sup>11</sup> Progress has been made. Many studies have numerous excursions, but the extent of these falls far short of what is needed.

<sup>12</sup> A series of RAND reports describes these methods and tools (Hillestad and Davis, 1998; Davis, 2002a; Davis, Kulick, and Egner, 2005). See also the broad discussion of related issues by MITRE (Kuskey, 2001).

<sup>13</sup> Variations of this depiction have appeared elsewhere (Davis, 2002a and 2004).

<sup>14</sup> The need for a family-of-tools approach—and the need in particular to give more emphasis to relatively simple, understandable, but far-reaching analytic methods—has been noted by others over time, including a Defense Science Board in 1996 and, in 2005, a Senior Advisory Group for M&S chaired by Admiral Dennis Blair of IDA.

<sup>15</sup> Exceptions exist. Some simple models are actually high-resolution specialty models, such as a model describing the kinematics of an individual missile impacting in an open area through which discrete armed vehicles are moving (Davis, Bigelow, and McEver, 2000).

<sup>16</sup> Current strategic simulations are, of course, imperfect. JICM lacks even an aggregate-level treatment of command and control; Thunder has a weak ground model and was intended for mission-level work; ITEM (Integrated Theater Engagement Model) is specialized to navy operations and is neither agile nor broad. JWARS is a much richer simulation than JICM, but it is much more appropriate for selective in-depth analysis than synoptic work or systems analysis, much less the exploratory analysis discussed in this paper. JWARS is being renamed by U.S. Joint Forces Command as the Joint Analysis System (JAS).

<sup>17</sup> A number of the relevant models or modeling systems are discussed briefly in another paper (Dechant et al., 2006). Analysis with such ABMs is not straightforward (Sanchez and Lucas, 2000).

<sup>18</sup> One example is analysis of ground combat with effects of missiles and aircraft, and with advanced tactics such as the use of robotics and precision weapons (Matsumura et al., 2000). Other examples include analysis with the venerable Brawler model of air-to-air engagements and analysis with the Naval Simulation System (NSS) (Stevens, 2000).

<sup>19</sup> Access to detailed models or their data is crucial even for higher-level analysis. A common problem with higher-level simple models is that they incorporate “naïve aggregations” that do violence to the problem, as when they assume perfect command and control or ignore underlying tactics, such as concentration of force. Better simple models incorporate factors reflecting the aggregate effect of such phenomena and the price of hedges.

For example, a simple model might have parameters that vary depending on whether one side or the other has information dominance. How to aggregate results of bottom-up agent-based modeling is not yet understood.

<sup>20</sup> Many good references exist, both classic and modern (Keegan, 1983; Gordon and Trainor, 2006). A new book describes human performance in military operations, both historical and experimental (Rowland, 2006).

<sup>21</sup> An example is the work of Dupuy (1987).

<sup>22</sup> Exceptions exist: the Army's Concepts Analysis Agency has long funded historical research; the Joint Staff's J-8 has long conducted war games (but not particularly to inform analysis); and many analysts outside of M&S groups build or use small spreadsheet-level models for particular purposes.

<sup>23</sup> Analysis can be and often is done without M&S. Simulations are merely a particular class of models that generate descriptions of system behavior over time.

<sup>24</sup> This point has been made repeatedly in review studies (National Research Council, 2004 and 2005; Davis, 2002a).

<sup>25</sup> Some discussions of adaptiveness associate it with learning, by analogy to how organisms "learn." In this paper, adaptiveness has a more general meaning that includes, e.g., preplanned contingency branches, a rough thinking-through of how to respond to surprise events, and "agility."

<sup>26</sup> The recent agent-based modeling literature is extensive and includes a review (Uhrmacher and Swartout, 2003), applications to military problems (Ilachinski, 2004; Horne and Leonardi, 2001), and social-network problems (Prietula, Carley, and Gasser, 1998), among others. Agents are discussed as well in a recent National Academy report (National Research Council, 2006).

<sup>27</sup> For example, a top-down agent architecture (i.e., "Belief, Desires, Intentions") has been applied to a social power structure (Taylor et al., 2004) and a traditional heavy agent architecture ("Soar") has been applied in social modeling (Carley and Prietula, 1993).

<sup>28</sup> An agent may, for example, reason with a small number of high-level factors and qualitative logic, rather much as a human decisionmaker summarizes reasoning before acting. The human may have gotten to that point by a far more tortuous path.

<sup>29</sup> One set of well-developed tools is Repast (North, Collier, and Vos, 2006), from the University of Chicago, and Argonne National Laboratory Source code is freely available at <http://repast.sourceforge.net> (as of December 18, 2006). We thank Peter Thompson (University of South Australia) and Mark Altaweel (Argonne National Laboratories) for information on Repast.

<sup>30</sup> Sponsored by the Office of Naval Research, one report (Taylor et al., 2002) describes a generic toolkit to visualize and report on the internal reasoning process of an intelligent agent. Also, artificial intelligence researchers at the Institute for Creative Technologies report on a framework to enable "explainable AI (XAI)" (Core et al., 2006).

<sup>31</sup> Game-theoretic methods have been used effectively within simulations—e.g., 1980s TAC-SAGE work at RAND led by Richard Hillestad and the even earlier SABER GRAND work in Air Force Studies and Analysis led by Major Leon Goodson (later Brigadier General) under Lieutenant Glenn Kent (2002).

<sup>32</sup> See the historical discussion in a recent biography of Herman Kahn (Ghamari-Tabrizi, 2005).

<sup>33</sup> These uses apply also to social-policy problems, as illustrated by so-called foresight methods (van de Riet, van het Loo, and Kahan, 2005; Kahan and Davis, 2006).

<sup>34</sup> A good deal of information about serious games can be found at [http://en.wikipedia.org/wiki/Serious\\_game](http://en.wikipedia.org/wiki/Serious_game) or at <http://www.seriousgames.org> (as of December 18, 2006).

<sup>35</sup> See discussion in Davis (2001, 2002b, and 2004).

<sup>36</sup> Red teams apply well to counterterrorism also, as demonstrated in a study led by James Miller (Murray, 2002 and 2003; Sinnreich, 2002; Murdock, 2003). The Defense Science Board has discussed red teaming at some length (Defense Science Board, 2003).

<sup>37</sup> The Army War College, for example, has long developed databases on what and how many forces have historically been used in various contingencies. A recent RAND study (Dobbins et al., 2003) reviews historical evidence on the perceived need for forces in the stabilization and reconstruction phases. Such studies sometimes fail to convince skeptics because they show what *was* used, rather than what was necessarily required or what may be needed today, but the information is nonetheless useful and often sobering.

<sup>38</sup> This is described in a short review paper (Davis, 2002b).

<sup>39</sup> Such operations were routine with the RAND Strategy Assessment System (RSAS), the broader predecessor to the current-day JICM. The RSAS had libraries of “analytic war plans” composed of building-block operations (Schwabe, 1990). The RSAS exploited a high-level language (RAND-Abel) and special structures motivated by artificial-intelligence research. JICM has an interface language that provides much of the same functionality (Jones, unpublished). The more detailed JWARS, now being tested by the U.S. Joint Forces Command and others, has significant capabilities for user-defined rules that exist in data and are easily changed (Burdick et al., 2002). These are compelling existence proofs of what can be done.

<sup>40</sup> The process of model, game, model has often been used effectively over the years, dating at least back to the predecessor of J-8 (SAGA). For many years, the most careful Joint Staff analyses were done with TACWAR used as a game board and bookkeeper, but with military officers making key decisions along the way, on both force employment and, sometimes, adjudication of results. The Joint Forces Command today uses a model-game-model approach.

<sup>41</sup> Modularity in complex systems was described well decades ago by Nobelist Herbert Simon (1981). A number of modern books deal with software development (Baldwin and Clark, 2000), sometimes under the rubric of component-based software (Szyperski, 2002).

<sup>42</sup> The state of the art in model composability has been reviewed recently for the DoD context, with many admonitions for pursuing it more effectively (Davis and Anderson, 2004; National Research Council, 2006).

<sup>43</sup> Another reason for “push back” against suggestions to emphasize modularity is that the interactions across a complex model, such as a strategic simulation, are numerous and important. Overzealous efforts to modularize can omit important relationships (as in limiting air-to-ground effects to direct killing of vehicles). With older technology, it was very difficult to deal well with modules having too many interactions. Today, that is much less so the case.

<sup>44</sup> An imperfect example is RAND’s START model, written as an Excel program. START was built as a specialty-program spin-off of JICM, one that made it easier to conduct various analyses for the U.S. Air Force. Originally, its predictions were identical to those of JICM for constant data; later, changes to START and JICM in different projects caused the models to diverge somewhat. If there were reasons to do so, minor reprogramming to reestablish complete consistency would probably be straightforward.

<sup>45</sup> The word “improve” is chosen carefully. There are practical limits on the degree of modularity that can be achieved in the big models because, as noted earlier, the number of interactions is large.

<sup>46</sup> Dell Lunceford refers to such models as “boutique models” and has long championed them in preference to continued exclusive emphasis on large, complex, and monolithic models.

<sup>47</sup> This is based on a comparison with the situation described in an early-1990s paper (Davis and Blumenthal, 1991), which was quite controversial at the time. The conclusions were subsequently reiterated and strengthened in a National Academy study (National Research Council, 1997).

<sup>48</sup> Other working groups focused on M&S for traditional and nontraditional warfare, respectively (Bracken et al., 2006; Dechant et al., 2006).