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Analysis, Analysis Practices, and Implications for Modeling and Simulation

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Prepared for the Office of the Secretary of Defense

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Summary

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 longstanding, 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: Resolution	Analytical: Agility	Analytical: Transparency	Scope	Phenomenology: Physical	Phenomenology: Human	Examples
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.

5	4	3	2	1
Very poor				Very good

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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
	Issue new VV&A guidelines for models intended for PMESII work	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
	Require serious treatment of future network-centric capabilities and implications	2	Commission competitive design for new or substantially reprogrammed campaign and mission-level models built around network centricity (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®[1] 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)[2] 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.