Operations Research for Deterrence and Strategic Influence Analysis

A Pilot Study

(b)(6) [redacted]

Innovative Decisions, Inc.

(b)(6) [redacted]

Science Applications International Corporation

(b)(6) [redacted]

Advanced Systems and Concepts Office
Defense Threat Reduction Agency

March 2010

The views expressed herein are those of the authors and do not necessarily reflect the official policy or position of the Defense Threat Reduction Agency, the Department of Defense, or the United States Government.

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Defense Threat Reduction Agency
Advanced Systems and Concepts Office
Report Number ASCO 2010 016
Contract Number DTRA01-03-D-0017, T.I. 18-06-17

The mission of the Defense Threat Reduction Agency (DTRA) is to safeguard America and its allies from weapons of mass destruction (chemical, biological, radiological, nuclear, and high explosives) by providing capabilities to reduce, eliminate, and counter the threat, and mitigate its effects.

The Advanced Systems and Concepts Office (ASCO) supports this mission by providing long-term rolling horizon perspectives to help DTRA leadership identify, plan, and persuasively communicate what is needed in the near term to achieve the longer-term goals inherent in the agency's mission. ASCO also emphasizes the identification, integration, and further development of leading strategic thinking and analysis on the most intractable problems related to combating weapons of mass destruction.

For further information on this project, or on ASCO's broader research program, please contact:

Defense Threat Reduction Agency
Advanced Systems and Concepts Office
8725 John J. Kingman Road
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ASCOInfo@dtra.mil

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Operations Research for Deterrence and Strategic Influence Analysis – A Pilot Study

Executive Summary

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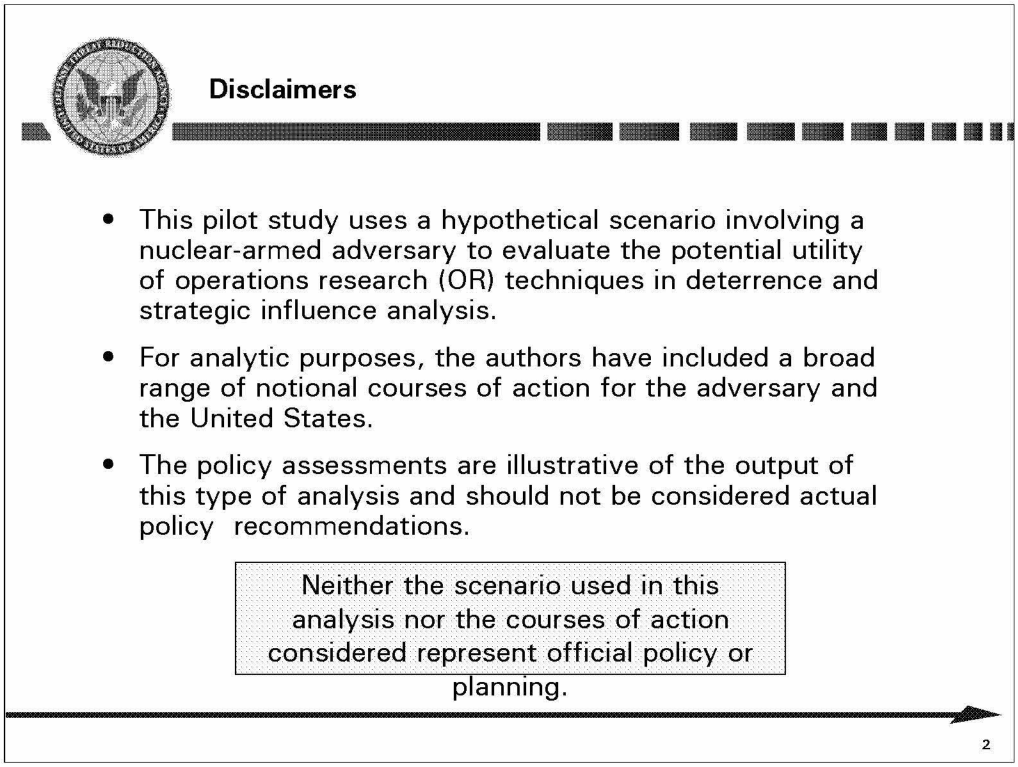
Deterrence analysis during the Cold War relied heavily on operations research. Throughout that era, a central core of quantitative analysis focused on nuclear strikes and counterstrikes with damage expectancy as a principal measure of effectiveness. Operations research techniques such as linear programming were employed to optimally assign weapons to targets subject to operational constraints and to evaluate damage to target sets. These calculations supported assessments of the adequacy of our nuclear forces to deter the Soviet Union and ancillary objectives such as maintaining first strike stability.

Now, two decades after the end of the Cold War, this calculus is largely irrelevant to today's deterrence challenges which focus more on rogue nations and terrorism than military peers. Recognizing the need for more relevant approaches, the United States Strategic Command (USSTRATCOM) has developed a qualitative methodology for deterrence analysis that relies on expert judgment rather than quantitative analysis.

While we acknowledge the limitations of nuclear exchange modeling in today's world, at least for rogue nations and terrorists, we are not as certain that qualitative methodologies cannot be usefully supplemented by the judicious application of appropriate operations research techniques. The purpose of this project is to explore this possibility—to what extent can operations research contribute to deterrence and influence analysis in a meaningful way?

It is not our expectation that the operations research techniques that were so widely used in the Cold War will be the same ones most useful today. An important and early part of the project was to identify the most promising candidates for examination. To facilitate an assessment of the utility and limitations of these techniques, we have applied them in a pilot study.

This project was conceived and funded by the Advanced Systems and Concepts Office (ASCO) of the Defense Threat Reduction Agency. It was executed as a collaboration among ASCO, Innovative Decisions, Inc., and Science Applications International Corporation. Earlier versions of this research were presented at the 2007 Military Operations Research Society (MORS) Symposium, the March 2008 MORS Deterrence Assessment Workshop, and the 2008 MORS Symposium. The views expressed herein are those of the authors and do not necessarily reflect the official policy or position of the Defense Threat Reduction Agency, the Department of Defense, or the United States Government.



We make the following disclaimers.

For this study, we developed a hypothetical scenario involving a (b)(5) [redacted] to evaluate the potential utility of operations research techniques in deterrence and strategic influence analysis. We selected (b)(5) [redacted] to make it timely and demanding. To test the robustness of the analysis techniques in demanding scenarios, we included a broad range of notional courses of action for both (b)(5) [redacted] and the United States. The unclassified, notional data we used for the hypothetical scenario and notional courses of actions produced analysis results that are illustrative of the output of this type of analysis. Therefore, the analysis and results should not be considered actual policy recommendations.

Neither the scenario used in this analysis nor the courses of action considered represent official policy or planning by any U.S. government agency.

Executive Summary contents*

- Audience
- Scope and terminology
- Motivation for operations research analysis
- Pilot study goals
- Framework to identify analysis tasks
- Integrated operations research analysis process
- Pilot study to test the process
  - Scenario
  - Qualitative analysis
  - Quantitative analysis
- Findings about the value of operations research

* A technical report is also available.

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This document provides an executive summary of the research. A technical report is also available on request from (b)(6) DTRA/ASCO, 703-767-5797. This chart provides the outline of the presentation.

We begin by defining the two primary audiences – consumers of deterrence analysis and leaders of Department of Defense (DoD) operations research organizations. Second, we define the scope and terminology of deterrence and deterrence options. (We note that deterrence operations are evolving to include decisive influence.) Third, we identify some of the challenges of deterrence and strategic influence analysis that motivate the potential need for operations research analysis. Fourth, we list our pilot study goals and emphasize that one of our goals is to compare the benefits and risks of qualitative and quantitative operations research techniques. Fifth, we describe the framework to identify deterrence analysis tasks. Sixth, we describe the integrated operations research analysis process we developed for several of the most promising techniques. Seventh, we describe the pilot study we conducted to achieve our analysis goal. We summarize the scenario and the qualitative and quantitative analysis we performed to support the selection of the U.S. courses of action in this scenario. Eighth, we present our findings about the value of qualitative and quantitative operations research methods. We conclude with potential next steps.

The audience for this briefing is consumers and providers of deterrence analyses

- Consumers
  - Senior strategic planners, operations planners, and intelligence analysts who provide courses of action and/or deterrence analyses to national security leaders
- Providers
  - Operations research leaders and analysts in OSD, Joint Staff, Combatant Commands, and Services

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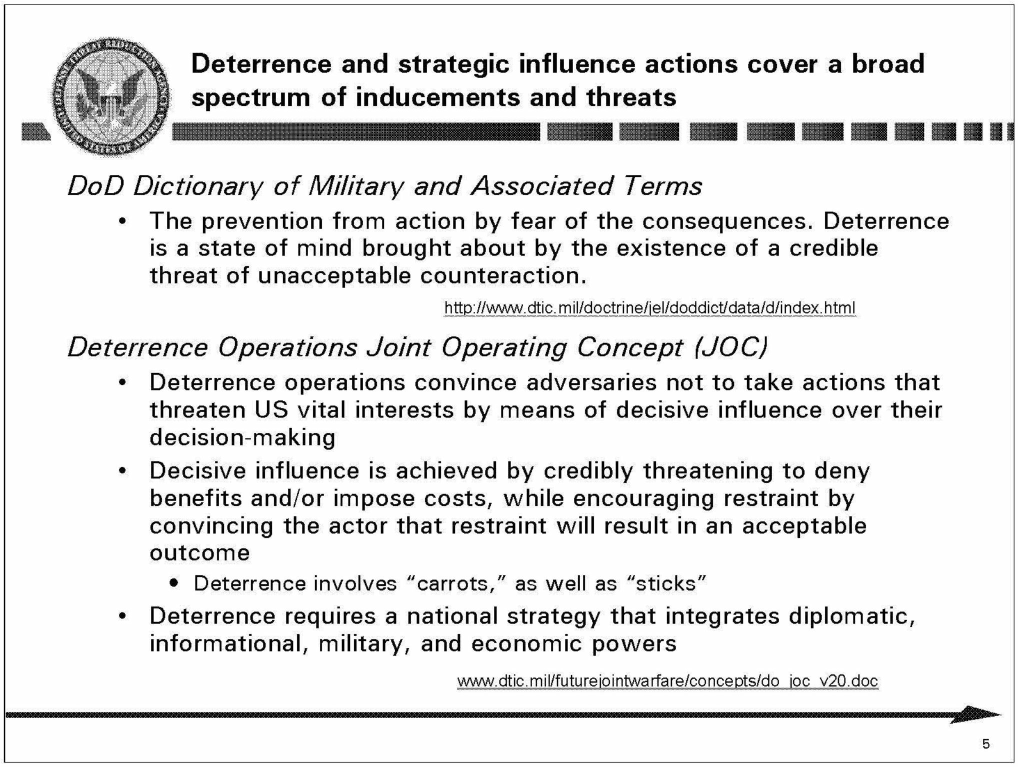
The audience for this briefing is consumers and potential providers of deterrence and influence analyses in DoD.

The potential consumers include senior strategic planners, military operations planners, and intelligence analysts who provide courses of action and/or deterrence and influence analyses to national security leaders.

The potential providers that could use these techniques include leaders and analysts of operations research in the Office of the Secretary of Defense (OSD), Joint Staff, Combatant Commands (especially U.S. Strategic Command), and the Armed Services.



We believe that deterrence is evolving to include strategic influence.

Potential adversary actions can affect U.S. vital interests and the ability of the United States to attain national objectives. The DoD dictionary definition of deterrence is "The prevention from action by fear of the consequences. Deterrence is a state of mind brought about by the existence of a credible threat of unacceptable counteraction."

http://www.dtic.mil/doctrine/jel/doddict/data/d/index.html

Early in a potential conflict, the United States may seek to influence adversary actions or deter specific actions that would threaten U.S. interests. Influence and deterrence are closely related. Davis and Jenkins develop an escalation ladder of coerciveness of influence. The ladder's rungs are distinguished by increasing violence. The ten steps are: co-opt, induce positively, persuade, dissuade, deter by threat, deter by increasing risks and disruption, deter by denial (defeat the attacks), deter next time by punishing now, deter next time by defeating now, and deter next time by crushing now. The U.S.'s understanding of the adversary's goals and objectives are important when considering what courses of action to take to influence and deter an adversary. This understanding develops as events unfold.

The Deterrence Operations Joint Operating Concept (Department of Defense, December 2006, page 3) uses this broader definition of deterrence that includes influence. The following three quotes emphasize the scope of deterrence envisioned by the document.

- Deterrence requires a national strategy that integrates diplomatic, informational, military, and economic power.
- Deterrence operations convince adversaries not to take actions that threaten U.S. vital interests by means of decisive influence over their decision-making.
- Decisive influence is achieved by credibly threatening to deny benefits and/or impose costs, while encouraging restraint by convincing the actor that restraint will result in an acceptable outcome.

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This study is motivated by the need to improve deterrence and strategic influence analysis

- Central to U.S. national security strategy during the Cold War, deterrence remains a critical component of U.S. national strategy in a changing context
  - Rather than focusing on one or two adversaries, deterrence must consider a wider spectrum of state and non-state actors
  - Rather than addressing only nuclear and large scale conventional attack, deterrence must address the full spectrum of weapons of mass destruction attacks that threaten U.S. vital interests
- Deterrence must be considered in the context of a much broader range of strategic influence options

This broader vision demands a wide spectrum of courses of action (COAs) that may benefit from use of OR for assessment.

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Deterrence was a key U.S. national security strategy during the Cold War. Cold War deterrence analysis involved conventional force-on-force combat modeling and nuclear exchange models to assess damage expectancy and first strike stability.

Deterrence remains a critical component of U.S. national strategy. However, the scope of deterrence is considerably broader now. The chart identifies three of the major differences between the cold war and our current challenges.

- Rather than focusing on one or two adversaries, deterrence must consider a wider spectrum of state and non-state actors
- Rather than addressing only nuclear or large-scale conventional attack, deterrence must address the full spectrum of weapons of mass destruction attacks that threaten U.S. vital interests
- Rather than relying principally on threats of massive retaliation, deterrence must consider a much broader range of inducements, threats, and actions

(b)(5)

Pilot study goals: We developed a research design to assess the potential benefit of OR techniques

- Defined deterrence analysis tasks
- Identified promising operations research techniques
- Integrated operations research models to provide a core deterrence analysis capability
- Developed a hypothetical scenario to evaluate techniques
- Developed qualitative and quantitative models
- Assessed benefits and costs for both types of models

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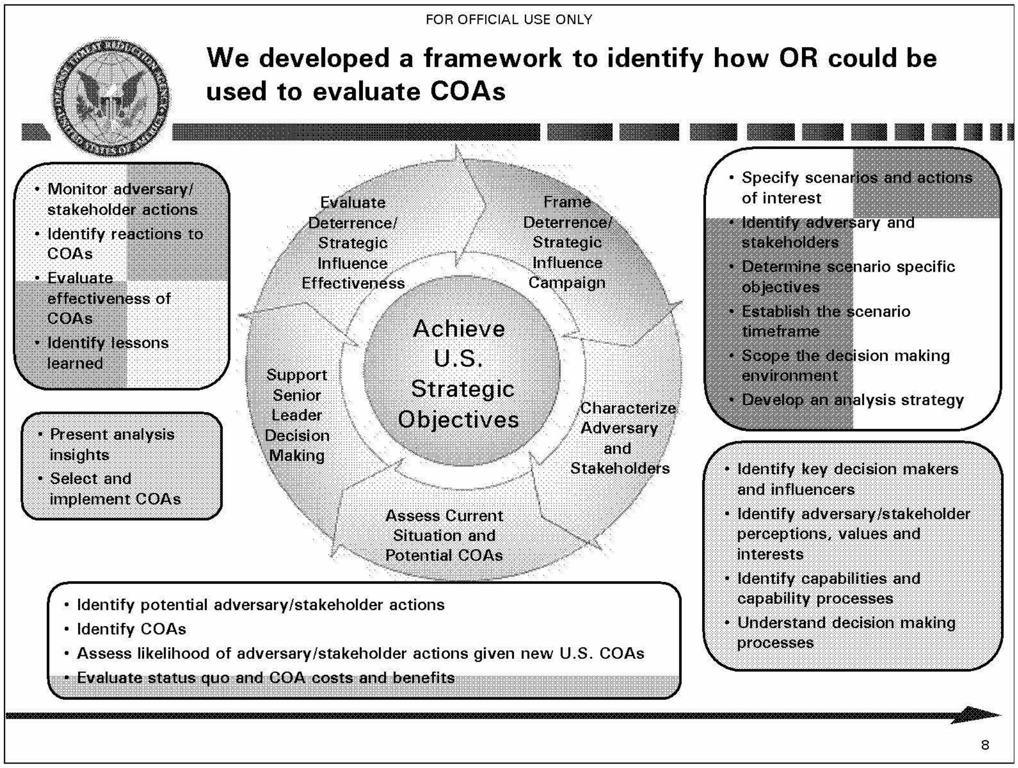
We developed our research design to assess the potential benefits and costs of operations research (OR) techniques.

First, we defined the deterrence and influence analysis tasks that would have to be performed in a deterrence campaign. We logically sequenced these tasks in a deterrence framework. Second, we identified the most promising operations research techniques for each task. Third, we selected a few of the most promising techniques. Using these, we developed an integrated deterrence analysis capability. Fourth, we created a demanding scenario to evaluate techniques. Fifth, we produced qualitative and quantitative models. We were specifically interested in assessing the ability of qualitative OR techniques to help identify the fundamental structure of the analysis and to provide a broad set of courses of action. Sixth, we carried out an illustrative analysis using a recognized subject matter expect. Finally, using the lessons learned from our research, we assessed the benefits and costs for both types of models from the perspective of subject matter experts, operations research analysts, and potential decision makers.

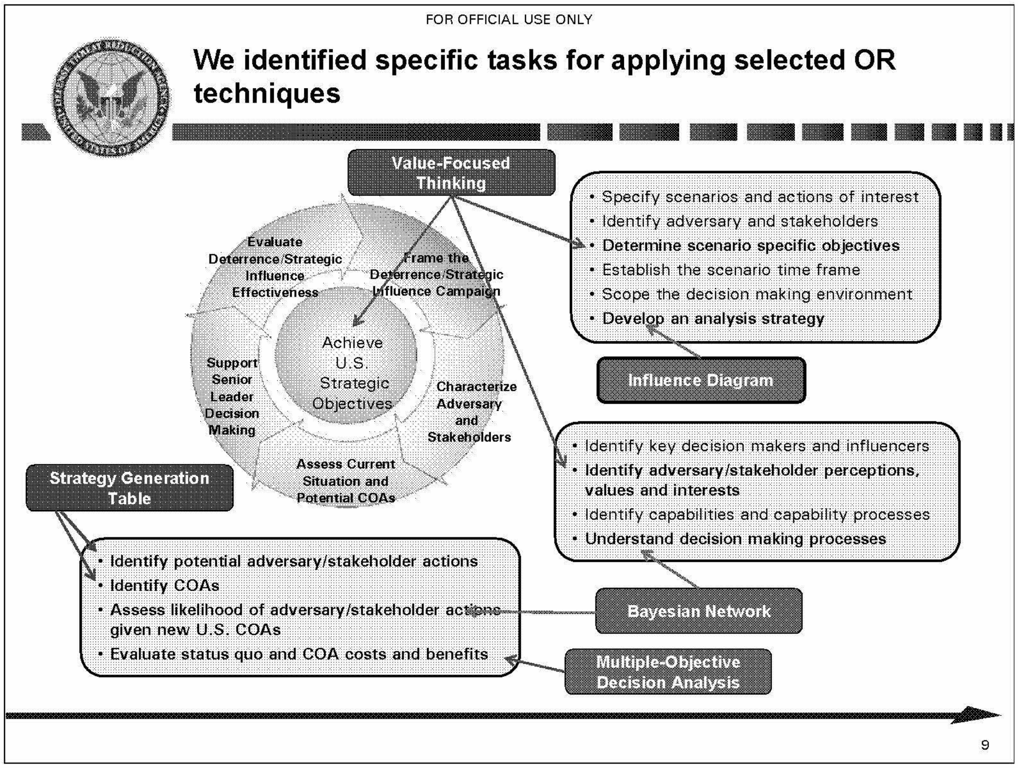


We created a deterrence campaign framework to identify analysis tasks supporting the development and evaluation of courses of action for national security leaders and joint combatant commanders. The framework was based primarily on the authors' experience providing analyses to senior decision makers. An important resource for the framework was the Deterrence Operations Joint Operating Concept (Department of Defense, December 2006). The center of the figure gives the purpose of the deterrence campaign: to achieve U.S. strategic objectives. This is our central focus. Around this purpose are the five iterative phases of the process. Each phase has multiple analysis tasks. The following is a brief summary of the iterative phases.

1. Frame the Deterrence/Strategic Influence Campaign – specify the deterrence scenarios of interest and the decisionmaking context
2. Characterize Adversary and Stakeholders – identify adversary/influencers and characterize perceptions, values, and interests. Also, where appropriate, characterize capability processes of concern (e.g., WMD development) that may be the focus of the Deterrence/Strategic Influence campaign
3. Assess Current Situation and Potential COAs – identify and evaluate adversary and U.S. COAs in light of the current circumstances
4. Support Senior Leader Decisionmaking – provide actionable insights to planners and decisionmakers
5. Evaluate Deterrence/Strategic Influence Effectiveness – evaluate deterrence effectiveness and identify lessons learned

We used the framework to identify the deterrence analysis tasks for each phase. These appear in the text boxes associated with each phase of the framework. We then used these tasks to identify the operations research techniques that could potentially be applied.

The charts that follow describe the major elements of the analysis and the results.



We used the *International Abstracts in Operations Research* Classification, and added risk analysis techniques, to identify 39 potential operations research techniques for deterrence analysis. We binned these into seven categories. The categories and the rationale for each are as follows.

- Uncertainty analysis – Deterrence involves significant uncertainties.
- Decision analysis – Deterrence involves complex alternatives, uncertainty, and major values. This is the exact focus of decision analysis.
- Gaming – Deterrence involves sequential actions/reactions of adversaries.
- Project management – Project management techniques can be used to assess the question of WMD acquisition that is often a central deterrence issue.
- Systems modeling and analysis – Deterrence involves complex systems interactions.
- Risk analysis – Deterrence presents risks to both adversaries.
- Portfolio analysis – A deterrence strategy can be considered a portfolio of actions.

The five most promising techniques were influence diagrams, value-focused thinking, COA (Strategy) generation tables, Bayesian networks (qualitative and quantitative), and multiple-objective decision analysis (MODA). This chart shows how these five techniques weere used for the analysis tasks of the deterrence framework for the (b)(5) [redacted] (b)(5) [redacted]

1. Value-focused thinking was used to integrate the strategic objectives and scenario-specific objectives for both the U.S. and the adversary. It was also used to identify adversary/stakeholder perceptions, values and interests.
2. An influence diagram was used to describe the deterrence analysis strategy.
3. Two strategy generation tables (one each for the U.S. and the adversary) were used to identify potential actions and to assemble COAs that considered diplomatic, informational, military, and economic actions.
4. Bayesian networks were used to understand the adversary decision making process and assess the likelihood of adversary/stakeholder actions given U.S. COAs.
5. Multiple-objective decision analysis was used to evaluate the costs and benefits of U.S. deterrence COAs compared to the status quo.

We designed an analysis process to integrate the selected techniques to identify the problem structure, develop COAs, and evaluate COAs. The technique names are listed on top of icons representing the analysis results (color coded by the analysis phases of the deterrence analysis framework). For example, the influence diagram was used to develop and describe the deterrence analysis strategy. By using the output of some OR models as inputs to other OR models, we were able to provide an integrated deterrence analysis capability.

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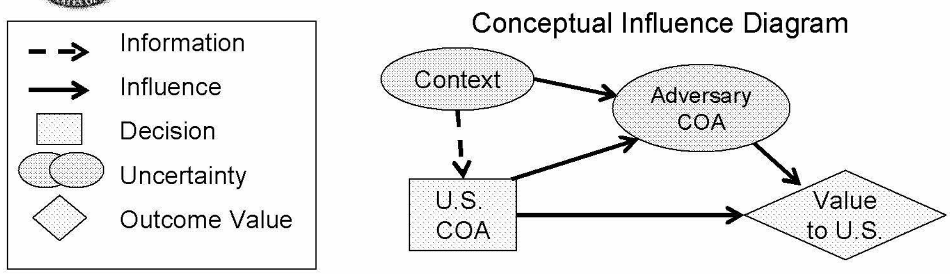
An influence diagram was used to guide the development of the operations research models



- Information about the context (including the scenario) is available to the both the U.S. and the adversary
- U.S. must consider the context and the potential impact of its COA on the adversary COA
- The context and the adversary COAs are uncertain
- The U.S. value of the outcomes depends on the actions of U.S. and adversary

The influence diagram icon is used to identify the focus of each subsequent analysis step.

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We used an influence diagram to guide the development of the operations research models. An influence diagram identifies decisions, uncertainties, and values. The influence diagram symbols are presented on the left. The dotted arrow for information indicates that information is known before the decision is made. The solid arrows representing influences, where the state of a preceding node affects the likelihoods of states in a following succeeding node, have a quantitative relationship The blue square represents a U.S. decision. The ovals represent uncertainties.

The conceptual influence diagram can be interpreted as follows. Information about the context (including the scenario) is available to the both the U.S. and the adversary. U.S. COAs must consider the context and the potential impact of its COA on the adversary COA. The context and the adversary COAs are uncertain. The value of the outcomes depends on the actions of the U.S. and the adversary.

For subsequent charts, the influence diagram icon is used to identify the focus of the analysis described on the chart.

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"*Take Away*": Qualitative OR techniques show promise for aiding deterrence/strategic influence analysis

- Value-focused thinking
  - Quickly establishes relative priority of U.S. objectives
  - Comparison with adversary objectives important to identifying likely flashpoints plus potential unanticipated threats
- Strategy generation tables
  - Helpful device for exploratory development of U.S./adversary COA across all instruments of national power
- Qualitative Bayesian network
  - Requires analyst to think through relationships in a structured way
  - Allows for greater complexity since it is qualitative
- However, refinement of qualitative OR techniques and deeper analysis of results needed to recommend a COA to decision makers

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We found that the analysis using the three qualitative operations research techniques (Value-focused thinking, COA generation table, and qualitative Bayesian networks) encouraged systematic thinking and provided some useful analysis insights.

The SME was able to provide the data and found the systematic thinking useful. The value hierarchy systematically defined the U.S. and adversary objectives and the range of potential outcomes. The strategy generation tables encouraged exploration of a wide range of COAs. Finally, the qualitative Bayesian network required the SME to identify in a structured manner the relevant context variables and dependencies among variables. Accordingly, the Bayesian network permitted a greater degree of complexity to be modeled.

The analysis team believes that the structured information could provide useful data for decisionmakers but that more analysis would be needed to recommend a COA. Furthermore, the qualitative analysis is an essential foundation for the subsequent quantitative analysis.

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***"Take Away":* Quantitative OR techniques are more suitable for informing deterrence analysts than as direct inputs to decision makers**

- Bayesian network – probability distributions
  - Complex elicitation process requires more experimentation by deterrence analysts to assess its utility for deriving policy recommendations
- Multiple-objective decision analysis model – elicited preferences
  - SME's freedom to set intervals helps to clarify how much better/worse one outcome is over another and, therefore, which outcomes merit higher priority in U.S. policy making
    - But, this is a subjective exercise that should be supplemented with peer review before results are presented to decision makers
- Combined approach
  - Large gap between even highest ranked and "Ideal" COAs suggests better policy options may be awaiting discovery and modeling by analysts
- Sensitivity analysis of assumptions is essential to improve model design and build analyst & decision maker confidence in the insights

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The SME offered the following insights on quantitative techniques that would be relevant to deterrence analysts, as well as decisionmakers.

Bayesian network – probability distributions:

- Shifting from a scale of 1 to 5 with fixed intervals in the semi-quantitative stage to a scale of <1 to 100 with no fixed intervals in the quantitative stage made for a more onerous, although in the end still manageable, elicitation process for the SME. To help manage this process, the SME did "copy" and "paste" some distributions to help populate the tables.
- Being able to refer back to COAs and previously-ordered likelihoods was essential to maintaining a degree of consistency in SME judgments, particularly as the elicitation sessions were spread out over many weeks due to other commitments. This leveraging of previous work was not without its downsides, however, as it risked replicating faulty assumptions.
- Overall, greater opportunities for the team to review output and experiment with the Bayesian network would have enabled the SME to form a more complete opinion as to its utility.

MODA model – elicited preferences:

- The freedom to set the intervals among the outcomes was a more direct expression of SME weighting. It helped the SME to clarify in his own thinking how much better/worse one outcome was over another and, therefore, which outcomes deserved higher priority in U.S. policy making. At the same time, this weighting represented the views of just one SME. To generate greater confidence in the MODA results, SME peer review of this weighting would be in order.

Combined approach:

- Of note to the SME was the gap between even the most promising U.S. COA (under semi-quantitative, full quantitative, or simplified quantitative) and the "Ideal" in this project. This gap may simply reflect an outcome where there are "no good options" for the U.S., given the complex interaction of U.S. and adversary COAs, as well as contextual factors. Alternatively, it may indicate that more "homework" is needed on the part of analysts, i.e., further identification of and experimentation with COAs should be undertaken in order to present a more complete picture of COA performance to decisionmakers.

Sensitivity analysis:

- It is essential to build in time to reflect on the analytical results. This then enables networks to be modified and new results to be generated. It likely would take multiple iterations to build up a deterrence analyst's confidence in the results to the level where they merited presentation to decisionmakers.

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"Final Take Away": Operations research techniques can enrich deterrence and strategic influence analysis

- Make SME's assumptions and judgments clear and explicit
  - Provide a qualitative analytic structure to identify the important context, value, and decision variables and their interrelationships
  - Enable elicitation of quantitative probability and value judgments
- Can be integrated into a complete analysis process
  - We integrated and leveraged COA generation table, value-focused thinking/multiple-objective decision analysis, and Bayesian networks
  - Other OR techniques (social networks, game theory, system dynamics, process modeling, etc) could also be integrated
- Support sensitivity analysis to identify critical judgments

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Operations research techniques can enrich deterrence analysis in the following ways.

First, OR techniques make the assumptions and judgments of a SME clear and explicit. They provide a qualitative analytic structure to identify the important context, value, and decision variables and their interrelationships, and they enable elicitation of quantitative probability and value judgments.

Second, OR techniques can be integrated into a complete analysis process. We integrated and leveraged COA generation table, MODA, and Bayesian networks. Other OR techniques (e.g., social networks, game theory, system dynamics, process modeling) could also be integrated into the methodology.

Finally, OR techniques support sensitivity analysis to test critical judgments.

Operations Research for Deterrence and Strategic Influence Analysis – A Pilot Study

Technical Report

(b)(6)

Innovative Decisions, Inc.

(b)(6)

Defense Threat Reduction Agency / Advanced Systems and Concepts Office

(b)(6)

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Disclaimers

- This pilot study uses a hypothetical scenario involving a nuclear-armed adversary to evaluate the potential utility of operations research (OR) techniques in deterrence and strategic influence analysis.
- For analytic purposes, the authors have included a broad range of notional courses of action for the adversary and the United States.
- The policy assessments are illustrative of the output of this type of analysis and should not be considered actual policy recommendations.

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Deterrence and strategic influence actions cover a broad spectrum of inducements and threats

DoD Dictionary of Military and Associated Terms

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http://www.dtic.mil/doctrine/jel/doddict/data/d/index.html

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  - Deterrence involves "carrots," as well as "sticks"
- Deterrence requires a national strategy that integrates diplomatic, informational, military, and economic powers

www.dtic.mil/futurejointwarfare/concepts/do_joc_v20.doc

3

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- Rather than addressing only nuclear or large-scale conventional attack, deterrence must address the full spectrum of weapons of mass destruction attacks that threaten U.S. vital interests
- Rather than relying principally on threats of massive retaliation, deterrence must consider a much broader range of inducements, threats, and actions

ASCO believes that the current vision of deterrence is much broader and requires the development of a commensurately broader set of analytic methods and tools for its assessment. This technical presentation focuses on the potential use of operations research techniques to help meet this challenge.

We developed a research design to assess the potential benefit of OR techniques

- Defined deterrence analysis tasks
- Identified promising operations research techniques
- Integrated operations research models to provide a core deterrence analysis capability
- Developed a hypothetical scenario to evaluate techniques
- Developed qualitative and quantitative models
- Assessed benefits and costs for both types of models

5

We developed our research design to assess the potential benefits and costs of operations research (OR) techniques.

First, we defined the deterrence and influence analysis tasks that would have to be performed in a deterrence campaign. We logically sequenced these tasks in a deterrence framework. Second, we identified the most promising operations research techniques for each task. Third, we selected a few of the most promising techniques. Using these, we developed an integrated deterrence analysis capability. Fourth, we created a demanding scenario to evaluate techniques. Fifth, we produced qualitative and quantitative models. We were specifically interested in assessing the ability of qualitative OR techniques to help identify the fundamental structure of the analysis and to provide a broad set of courses of action. Sixth, we carried out an illustrative analysis using a recognized subject matter expect. Finally, using the lessons learned from our research, we assessed the benefits and costs for both types of models from the perspective of subject matter experts, operations research analysts, and potential decision makers.

The audience for this technical report is a deterrence analyst or an OR analyst

- Deterrence analyst assumptions
  - Experience as a deterrence analyst
  - Background in qualitative analysis
  - Receptive to quantitative analysis techniques
- OR analyst assumptions
  - Limited understanding of deterrence analysis
  - Background in quantitative analysis
  - Receptive to qualitative or semi-quantitative analysis
- Common assumptions
  - Understanding of probability theory and Monte Carlo simulation
  - Little knowledge of strategy generation tables, multiple-objective decision analysis, Bayesian networks, and expert elicitation of probabilities

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This is a technical presentation designed for two audiences.

The first audience is deterrence analysts interested in learning new techniques. We assume deterrence analysts have experience with some analytic methods, a background in qualitative analysis, and are receptive to learning new semi-quantitative and quantitative analysis techniques.

The second audience is operations research analysts. We assume OR analysts may have a limited understanding of deterrence, a background in quantitative analysis, and are receptive to learning new qualitative and semi-quantitative techniques.

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Report contents

Slide

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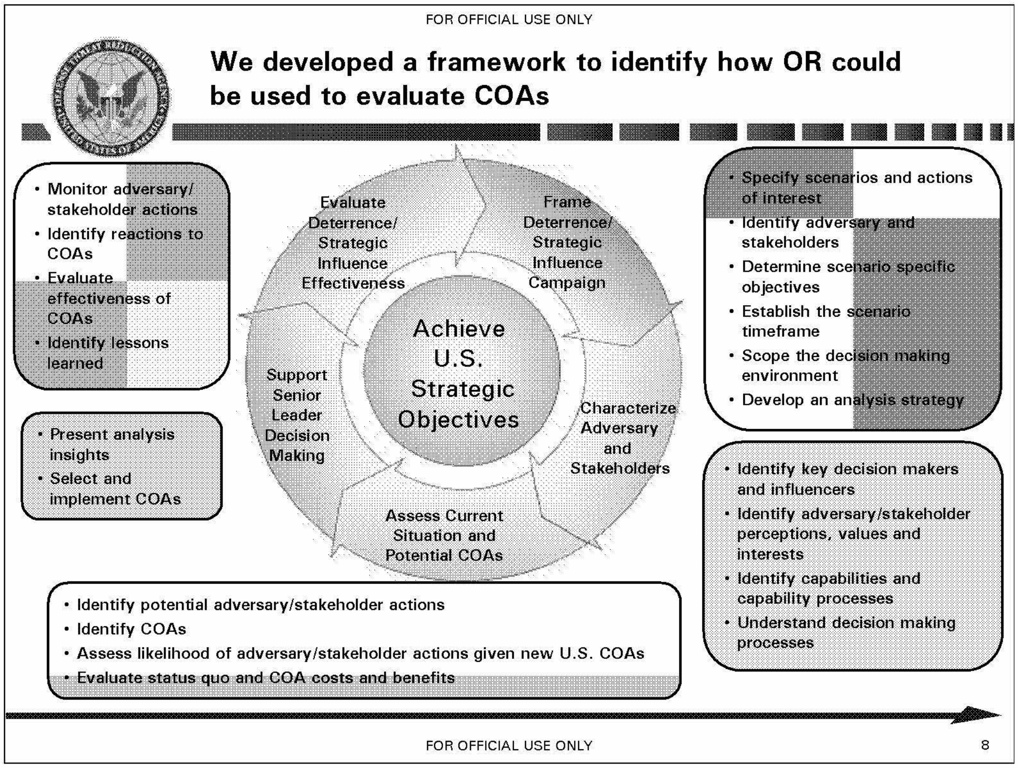
This slide provides an overview of the technical presentation. The presentation has three sections: background; pilot study; and results and findings, including future steps.

We begin with a description of the Deterrence/Strategic Influence campaign framework that we developed to identify the tasks that analysts could use operations research techniques to investigate. Next, we summarize a notional deterrence assessment we performed using a (b)(5) [redacted] scenario based on illustrative data obtained from a literature analysis. One of the critical concerns was the amount of expert/decision maker time that operations research techniques would require. This preliminary analysis led us to conduct a pilot study with a more realistic scenario and a subject matter expert. We wanted to assess the value added of additional SME time.

The second and most extensive section of the presentation is the pilot study, which focuses on a (b)(5) [redacted] scenario. First, we discuss the scenario assumptions. Second, we provide an overview of the methodology, which integrates operations research techniques. Next, we describe in detail the three levels of analysis: qualitative, semi-quantitative, and quantitative. The qualitative analysis used no numbers. The semi-quantitative analysis used numbers from algorithms that required little additional expert input. The quantitative analysis provides the full analysis with quantitative assessments from the SME. Each of these three analyses provides a summary of findings, including a discussion of conflicting results.

The third section presents overall study results and findings concerning the utility of using operations research for deterrence analysis. We conclude with a discussion of future steps.



We created a deterrence campaign framework to identify analysis tasks supporting the development and evaluation of courses of action for national security leaders and joint combatant commanders. The framework was based primarily on the authors' experience providing analyses to senior decision makers. An important resource for the framework was the Deterrence Operations Joint Operating Concept (Department of Defense, December 2006). The center of the figure gives the purpose of the deterrence campaign: to achieve U.S. strategic objectives. This is our central focus. Around this purpose are the five iterative phases of the process. Each phase has multiple analysis tasks. The following is a brief summary of the iterative phases.

1. Frame the Deterrence/Strategic Influence Campaign – specify the deterrence scenarios of interest and the decisionmaking context
2. Characterize Adversary and Stakeholders – identify adversary/influencers and characterize perceptions, values, and interests. Also, where appropriate, characterize capability processes of concern (e.g., WMD development) that may be the focus of the Deterrence/Strategic Influence campaign
3. Assess Current Situation and Potential COAs – identify and evaluate adversary and U.S. COAs in light of the current circumstances
4. Support Senior Leader Decisionmaking – provide actionable insights to planners and decisionmakers
5. Evaluate Deterrence/Strategic Influence Effectiveness – evaluate deterrence effectiveness and identify lessons learned

We used the framework to identify the deterrence analysis tasks for each phase. These appear in the text boxes associated with each phase of the framework. We then used these tasks to identify the operations research techniques that could potentially be applied.

We identified OR techniques and theories that could be useful for deterrence analysis

	Categories						
	Uncertainty Analysis	Decision Analysis	Gaming	Project Management	Systems Modeling and Analysis	Risk Analysis	Portfolio Analysis
Techniques / Theories	Scenario analysis Probability theory Bayesian networks Forecasting Statistical inference Fuzzy logic Dempster Shafer theory Possibility theory	Value-focused thinking Multiple-objective decision analysis Multiple-attribute value/utility theory Multiple-criteria decision making Prospect theory Decision tree Influence diagram Dynamic decision network Strategy generation table	Games Game theory Negotiation theory	Work breakdown structure Organization chart Process modeling Critical Path Method/ Program Evaluation and Review Technique Project risk management	Discrete event simulation System dynamics Agent-based simulation Monte Carlo simulation Social network analysis Cognitive modeling / map Input-output modeling	Probabilistic risk analysis Risk matrix Fault, event, and attack tree Failure modes and effects analysis	Benefit/cost analysis Mathematical programming Portfolio theory
	Expert judgment elicitation						

Selected for pilot study — Supporting technique

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We used the *International Abstracts in Operations Research* Classification and added risk analysis techniques to identify a list of potential operations research techniques for deterrence analysis. We binned a set of promising techniques into the seven categories shown on this chart; the rationale for each category is provided below.

Uncertainty analysis – Deterrence involves significant uncertainties.

Decision analysis – Deterrence involves complex alternatives, uncertainty, and major values. This is the exact focus of decision analysis.

Gaming – Deterrence involves sequential actions/reactions of adversaries.

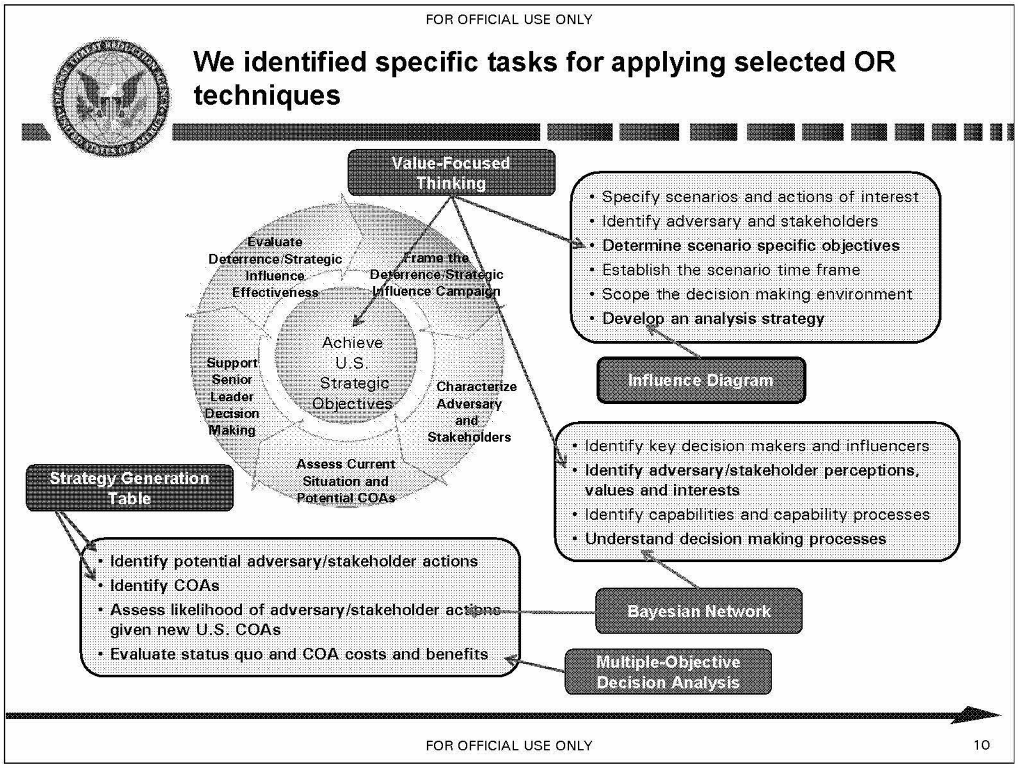
Project management – Project management techniques can be used to assess the question of WMD acquisition that is often a central deterrence issue.

Systems modeling and analysis – Deterrence involves complex systems interactions.

Risk analysis – Deterrence presents risks to both adversaries.

Portfolio analysis – A deterrence strategy can be considered a portfolio of actions.

In bold red are the core techniques selected for use in the pilot study. In light blue are supporting techniques.



This chart depicts how the five selected operations research techniques were used in the analysis tasks of the deterrence framework for the notional (b)(5) [redacted] scenario and the pilot (b)(5) [redacted] scenario.

Value-focused thinking was used to integrate the strategic objectives and scenario-specific objectives for both the U.S. and the adversary. It was also used to identify adversary/stakeholder perceptions, values and interests.

An influence diagram was used to describe the deterrence analysis strategy.

Two strategy generation tables (one each for the U.S. and the adversary) were used to identify potential actions and to assemble COAs that considered diplomatic, informational, military, and economic actions.

Bayesian networks were used to understand the adversary decision making process and assess the likelihood of adversary/stakeholder actions given U.S. COAs.

Multiple-objective decision analysis was used to evaluate the costs and benefits of U.S. deterrence COAs compared to the status quo.

We designed an analysis process to integrate the selected techniques to identify the problem structure, develop COAs, and evaluate COAs. The technique names are listed on top of icons representing the analysis results (color coded by the analysis phases of the deterrence analysis framework). For example, the influence diagram was used to develop and describe the deterrence analysis strategy. By using the output of some OR models as inputs to other OR models, we were able to provide an integrated deterrence analysis capability.

(b)(5)

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We learned that the use of OR techniques for deterrence analysis has strengths and limitations

Strengths

- Several operations research techniques are applicable to deterrence analysis tasks
- It is feasible to integrate a few operations research techniques into a deterrence analysis capability
- Use of operations research techniques makes assumptions, values, objectives, relationships, and alternatives explicit

Limitations

- Requires access to senior leaders and subject matter experts (SMEs) to obtain context, objectives and probabilities
- Explaining techniques to audiences with or without a strong background in operations research is challenging
- (b)(5) [redacted] scenario lacked nuance, did not use SMEs, and was thus inadequate to assess operational use.

These lessons motivated us to

- Use a more realistic scenario
- Use subject matter experts
- Find ways to simplify data requirements
- Provide clear explanations of assumptions and analysis
- Demonstrate that new insights could be provided

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Through the notional (b)(5) [redacted] scenario, we learned that using OR techniques for deterrence analysis has both strengths and limitations.

Strengths

- Several OR techniques are applicable to deterrence analysis tasks.
- It is feasible to integrate the five selected OR techniques into a deterrence analysis capability.
- Using OR techniques makes assumptions, values, objectives, relationships, and alternatives explicit.

Limitations

- Using OR requires access to senior leaders and subject matter experts to obtain context, objectives, and probabilities.
- Explaining techniques to audiences without a strong background in OR is challenging.
- The (b)(5) [redacted] scenario lacked nuance, did not use SMEs, and was thus inadequate to assess operational use in a robust way.

These lessons motivated us to

- Use a more realistic scenario (we selected an (b)(5) [redacted] scenario).
- Use subject matter experts.
- Find ways to simplify data requirements (qualitative and semi-quantitative models).
- Provide clear explanations of the assumptions and analysis.
- Demonstrate that new insights could be provided.

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Report contents

- Background
  - Deterrence/**Strategic Influence** campaign framework
  - Notional (b)(5) [redacted] scenario
- Pilot study – (b)(5) [redacted]
  - Adversary profile and scenario
  - Overview of methodology
  - Qualitative analysis
  - Semi-quantitative analysis
  - Quantitative analysis
- Results and findings

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Having completed our description of the deterrence campaign framework and the initial (b)(5) [redacted] scenario, we now turn to the more extensive pilot study scenario.

We provide the scenario and adversary profile, followed by an overview of the methodology. Next, we describe in detail the three levels of analysis: qualitative, semi-quantitative, and quantitative. The qualitative analysis uses no numbers. The semi-quantitative analysis uses numbers but in the form of algorithms that demand little additional input from the experts. The quantitative analysis provides reflects quantitative inputs from the SME. In each of these discussions we provides a summary of findings, including a discussion of conflicting results.

The final section presents overall pilot study results and findings about the potential value of using OR for deterrence analysis. We conclude with a discussion of future steps.

(b)(5)

(b)(5)

(b)(5)

(b)(5)

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Report contents

- Background
  - Deterrence campaign framework
  - Notional (b)(5) [redacted]
- Pilot study – (b)(5) [redacted]
  - Adversary profile and scenario
  - Overview of methodology
  - Qualitative analysis
  - Semi-quantitative analysis
  - Quantitative analysis
- Results and findings

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Having completed our discussion of the (b)(5) [redacted], we now provide an overview of the methodology, including the integration of the operations research techniques we used in the analysis.

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We used the lessons learned from the notional scenario to enhance the pilot study

- Developed a richer, more nuanced scenario
- Worked with a subject matter expert throughout the study
- Explored impact of simpler data requirements by creating deterrence models at three levels of quantification
- Developed this detailed technical report and an executive summary to explain the analysis process

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We used the lessons learned from the notional scenario to enhance the pilot study. First, we adapted a previously developed realistic deterrence scenario. Second, we worked with a subject matter expert throughout the study. Third, we explored the impact of simpler data requirements by creating deterrence models at three levels of quantification: qualitative analysis, semi-quantitative analysis, and quantitative analysis. Fourth, we developed this detailed presentation to explain the process.

COAs were evaluated using three levels of analysis

- Qualitative
  - Develop COAs
  - Elicit qualitative (non-numeric) expert judgments about variables and preferences
  - Qualitatively evaluate COAs
- Semi-quantitative
  - Build on qualitative models
  - Order the likelihood of outcomes
  - Use algorithms to convert orderings to numeric values
  - Quantitatively evaluate COAs
- Quantitative
  - Build on qualitative and semi-quantitative models
  - Elicit probabilities and quantitative values
  - Quantitatively evaluate COAs

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It became apparent during the development of the operation research models for the notional (b)(5) [redacted] that understanding the context, identifying variables, identifying objectives, and quantifying probabilities and assessing values would require significant and time-consuming interaction with SMEs.

To assess the value added of the additional SME effort, we planned for three levels of analysis: qualitative, semi-quantitative, and quantitative.

The qualitative analysis is non-numeric and includes identifying and defining context variables, strategic and scenario objectives, value hierarchy and value measures, value measure outcomes, and courses of action. The analysis concludes with a qualitative evaluation of the COAs.

The semi-quantitative analysis is numeric but uses algorithms to minimize the required interaction with SMEs. The semi-quantitative analysis builds on the qualitative models, asks the SME to rank-order likelihoods/probabilities and importances, and uses algorithms to convert likelihoods and importance orderings to numeric values. This analysis concludes with a quantitative evaluation of the COAs.

The quantitative analysis builds on the qualitative and semi-quantitative models, but replaces the algorithms with elicited probabilities, weights and value functions from the SME. This analysis concludes with a more granular quantitative evaluation of the COAs.

The SME was a key participant in the analysis team

- We used SME information for all three levels of analysis
- Qualitative analysis
  - Model structure
    - Value hierarchy for U.S. and (b)(5)
    - COA generation table structuring
    - Value measure scale definitions
  - Most likely outcomes on value measures
  - Ordering relative importance of value measures
- Semi-quantitative analysis
  - Ordering likelihood of outcomes
- Quantitative analysis
  - Value measure weights
  - Value function parameters
  - Probability distributions

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The SME was fully integrated into the study effort. We used his expertise in all phases of model development. His inputs were used whenever judgments were needed to develop the model structure, to rank order weights and likelihoods, and whenever numerical quantities were required.

Report Contents

- Background
  - Deterrence campaign framework
  - Notional (b)(5)
- Pilot study – (b)(5) scenario
  - Adversary profile and scenario
  - Overview of methodology
  - Qualitative analysis
  - Semi-quantitative analysis
  - Quantitative analysis
- Results and findings

The qualitative analysis is presented first.

We developed a conceptual influence diagram

OR Technique	Level of Analysis		
	Qualitative	Semi-Quantitative	Quantitative
Influence Diagram	Conceptual Influence Diagram		
Value-Focused Thinking	Qualitative Value Model		
COA Generation Table	U.S. COA Generation Table / (b)(5) Generation Table		
Bayesian Network	Baseline Bayesian Network	Simplified Bayesian Network (Ordered Likelihoods)	Simplified Bayesian Network (Probability Distributions)
Multiple Objective Decision Analysis	Simplified Value Model (Dominance Analysis)	Baseline MODA Model (Algorithmic Preferences)	Baseline & Simplified MODA Model (Elicited Preferences)

This table presents the models and elicitation techniques used in the pilot study, in the order in which they were developed (top to bottom and left to right).

In the introduction of each section, this slide highlights in yellow the model described in the section. Each model is indexed by its OR technique and level of analysis. For example, this slide introduces a section describing the Conceptual Influence Diagram. It is a technique used in all three levels of analysis. The table also notes the types of analytic outputs derived from the technique.

Qualitative models were developed before semi-quantitative models. For example, The baseline Bayesian Network was developed before the Qualitative Value Model. These were both completed before proceeding to the semi-quantitative versions of the simplified Bayesian network and multiple-objective decision analysis (MODA) Model.

The differences between the semi-quantitative and quantitative versions of the simplified Bayesian Networks and MODA Models is in the level of refinement of probabilities, weights, and values as indicated by the items in parentheses.

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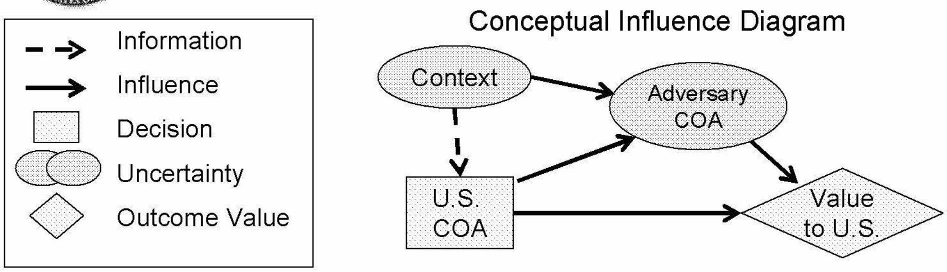
An influence diagram was used to guide the development of OR models



- Information about the context (including the scenario) is available to the both the U.S. and the adversary
- U.S. must consider the context and the potential impact of it's COA on the adversary COA
- The context and the adversary COAs are uncertain
- The U.S. value of the outcomes depends on the actions of the U.S. and the adversary

The influence diagram icon is used to identify the focus of each subsequent analysis step.

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The influence diagram identifies the classes of decisions, uncertainties, and values to be considered in developing the OR models. In this case, we are interested in how a choice of a U.S. COA impacts the actions of (b)(5) We know that the context of the situation, as well as the U.S. COA itself, influences (b)(5) choice of COA. We want to choose a U.S. COA that maximizes the value to the U.S. Because any U.S. decision has its own costs and benefits, both the U.S. and (b)(5) actions influence the value node.

Information available to the U.S. supports inferences about the context within which the adversary makes decisions.

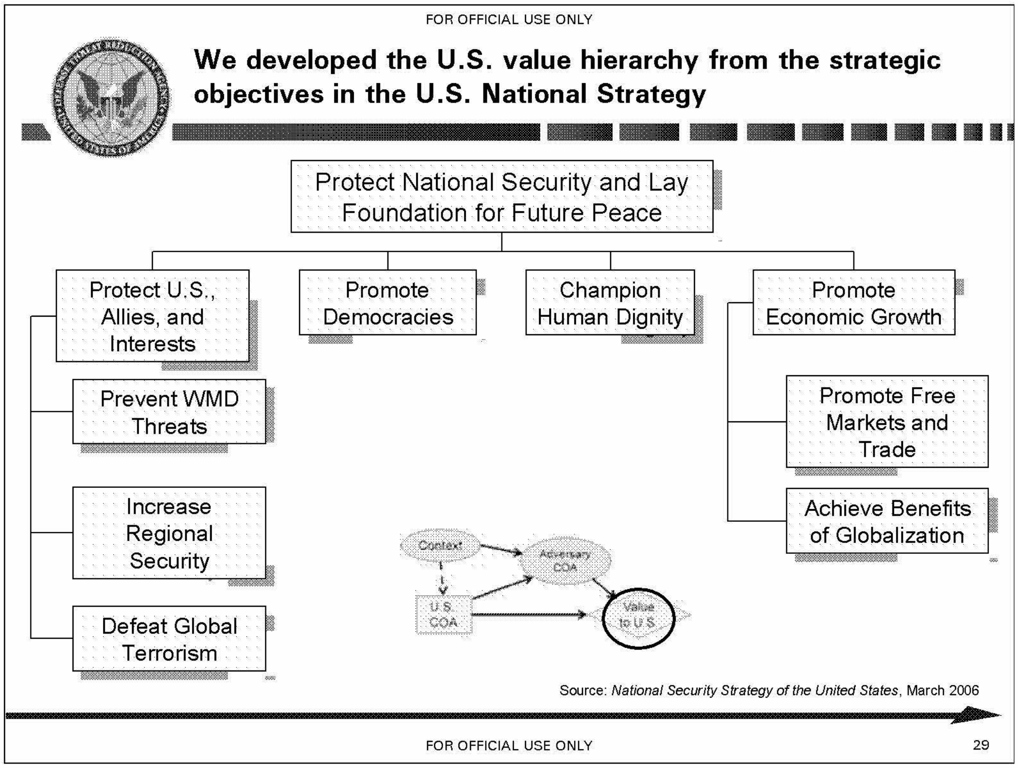
The dotted line for information simply indicates that the U.S. is making inferences about the situation from available data that is known <u>before</u> the decision is made. That data is uncertain and incomplete, which is why the context is uncertain. In the modeling process, the dotted line is not modeled.

We developed a U.S. value hierarchy using value-focused thinking

OR Technique	Level of Analysis		
	Qualitative	Semi-Quantitative	Quantitative
Influence Diagram	Conceptual Influence Diagram		
Value-Focused Thinking	Qualitative Value Model		
COA Generation Table	U.S. COA Generation Table / (b)(5) Generation Table		
Bayesian Network	Baseline Bayesian Network	Simplified Bayesian Network (Ordered Likelihoods)	Simplified Bayesian Network (Probability Distributions)
Multiple Objective Decision Analysis	Simplified Value Model (Dominance Analysis)	Baseline MODA Model (Algorithmic Preferences)	Baseline & Simplified MODA Model (Elicited Preferences)

In this section, we introduce the U.S. Value Hierarchy and define the value measures associated with the hierarchy. We elicited these items from the SME. We also asked the SME to give us a preference order over the outcomes of the values.

The U.S. Value Hierarchy and associated value measures apply to all three levels of analysis. We make use of the value measures in subsequent Bayesian Network and MODA models.



We developed a value hierarchy based on the U.S. Strategic Objectives. The value hierarchy relates the overall goal of promoting U.S. interests to more specific goals that can be used as a basis for comparing COAs.

We used the "gold standard" technique (Parnell, in Loerch and Rainey, 2007) where a value structure is developed based on an approved vision, policy, strategy, planning, or doctrine document. We used the *National Security Strategy of the United States* (March 2006). The specific wording of the National Strategy is paraphrased as follows.

- Champion Human Dignity: Champion aspirations for human dignity.
- Defeat Global Terrorism: Strengthen alliances to defeat global terrorism and work to prevent attacks against U.S. and our friends.
- Increase Regional Security: Work with others to defuse regional conflicts.
- Prevent WMD Threats: Prevent our enemies from threatening us, our allies, and our friends with weapons of mass destruction (WMD).
- Promote Economic Growth/Promote Free Markets and Trade: Ignite a new era of global economic growth through free markets and free trade.
- Promote Democracies: Expand the circle of development by opening societies and building the infrastructure of democracy.
- Achieve Benefits of Globalization: Engage the opportunities and confront the challenges of globalization.
- NA: Develop agendas for cooperative action with other main centers of global power.
- NA: Transform America's national security institutions to meet the challenges and opportunities of the 21st century.

Parnell, G.S., *Chapter 19, Value-Focused Thinking*, Methods for Conducting Military Operational Analysis, Military Operations Research Society, Editors Larry Rainey and Andrew Loerch, 2007, pp. 619-656.

(b)(5)

(b)(5)

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We developed U.S. (b)(5) COAs using strategy generation tables

OR Technique	Level of Analysis		
	Qualitative	Semi-Quantitative	Quantitative
Influence Diagram	Conceptual Influence Diagram		
Value-Focused Thinking	Qualitative Value Model		
COA Generation Table	U.S. COA Generation Table / (b)(5) Generation Table		
Bayesian Network	Baseline Bayesian Network	Simplified Bayesian Network (Ordered Likelihoods)	Simplified Bayesian Network (Probability Distributions)
Multiple Objective Decision Analysis	Simplified Value Model (Dominance Analysis)	Baseline MODA Model (Algorithmic Preferences)	Baseline & Simplified MODA Model (Elicited Preferences)

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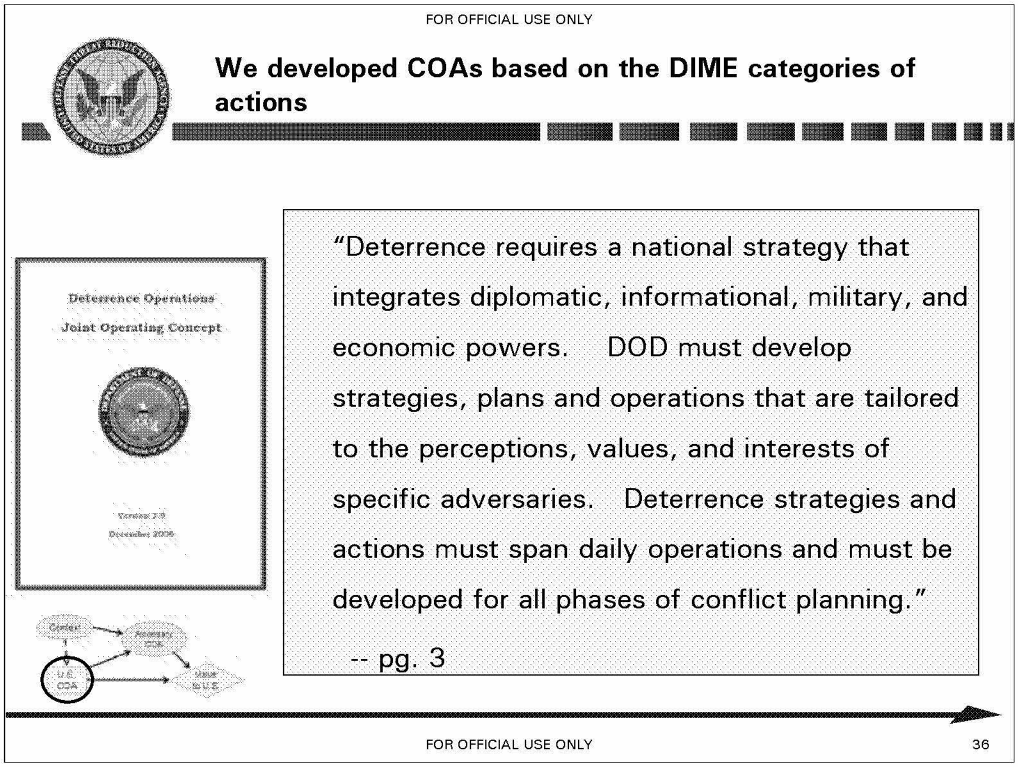
In this section, we develop the courses of action (COAs) for both the U.S. (b)(5) The generated COAs are used in all subsequent Bayesian network and MODA models.



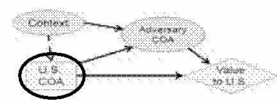
The Deterrence Operations Joint Operating Concept (Department of Defense, December 2006) provides guidance for the development of courses of action. On page 3, it reads:

"Deterrence requires a national strategy that integrates diplomatic, informational, military, and economic (DIME) powers. DOD must develop strategies, plans and operations that are tailored to the perceptions, values, and interests of specific adversaries. Deterrence strategies and actions must span daily operations and must be developed for all phases of conflict planning."

Therefore, we developed COA generation tables based on the DIME categories of actions. The strategy generation table method is described on the next chart.

COA generation tables combine specific options into integrated courses of action

- Generate options for each DIME category. Options may
  - Convey intent
  - Deny benefits of harmful adversary actions
  - Reduce likelihood of adversary success
  - Increase or decrease U.S. capabilities
  - Decrease adversary capabilities
  - Etc.



- Identify integrated COAs as combinations of options from the DIME categories
  - Multiple options (e.g. M1, M2) may be selected from a DIME

Course of Action	Diplomatic	Informational	Military	Economic
	D1		M1	
COA Alpha		I2	M2	
				E3

COA generation tables are more commonly known as Strategy Generation Tables (Parnell, in Loerch and Rainey, 2007), or in the systems analysis community as Zwicky's Morphological Box (Buede, 2000). The COA generation table is a technique for developing COA alternatives as combinations of related options. We developed options in the categories of Diplomatic, Informational, Military and Economic actions.

We worked with the SME to develop a range of options in each category, ranging from options that would tend to appease (b)(5) [redacted] to more aggressive options that would directly confront or attack Iran. Many of the options had been developed in previous work done by the SME (Giles, et. al., 2005). Each COA is comprised of one or more options from each of the DIME categories, selected to be compatible with one another both in the sense that they could be performed as a group and that they represented similar approaches to dealing with (b)(5) [redacted]

The next slide shows the details of a particular COA and the slide following that summarizes the seven COAs developed for the pilot study.

References:

Dennis Buede, The Engineering Design of Systems: Models and Methods. (John Wiley and Sons, New York, 2000.)

Gregory F. Giles, Dr. Lewis A. Dunn, Jack Boureston, Lindsay Fritz, Dr. Jennifer S. H. Morstein, and Suzannah Sennetti, Assessing the threat of Iran WMD proliferation: Possible U.S. courses of action to address acquisition, transfer, use, and rollback. (SAIC, McLean, VA, 2005.)

Andrew G. Loerch, Larry B. Rainey (eds.). Methods for Conducting Military Operational Analysis. (Military Operations Research Society, LMI Research Institute, 2007.)

(b)(5)

(b)(5)

(b)(5)

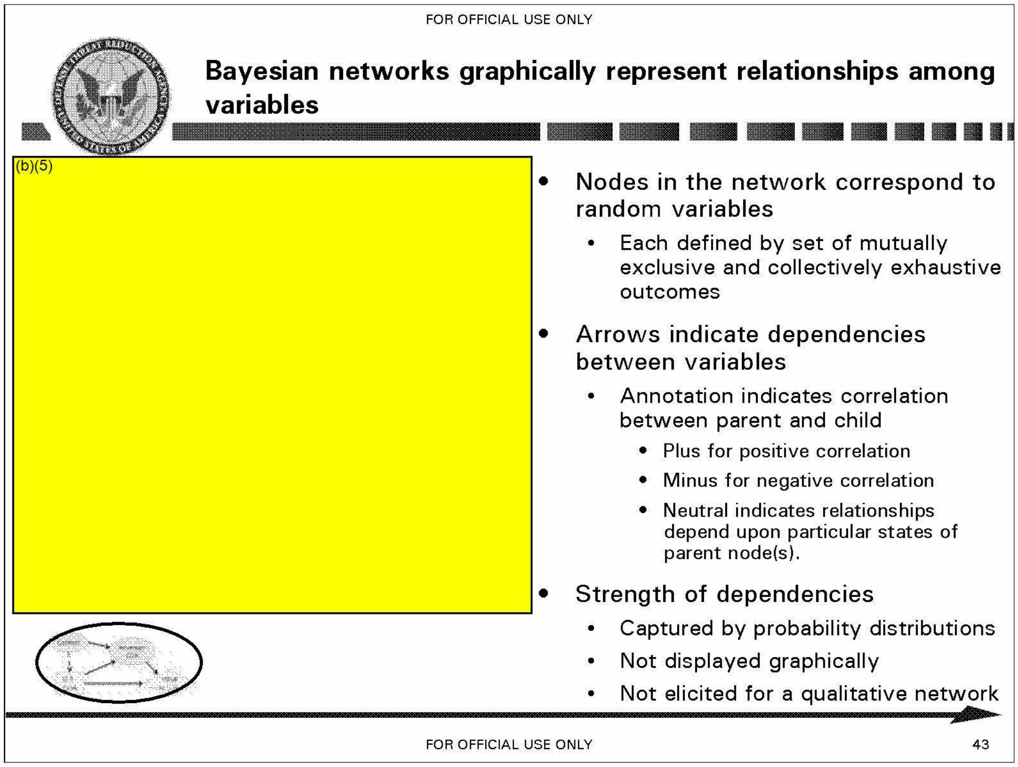
(b)(5)

We developed a qualitative Bayesian network

OR Technique	Level of Analysis		
	Qualitative	**Semi-Quantitative**	**Quantitative**
Influence Diagram	Conceptual Influence Diagram		
Value-Focused Thinking	Qualitative Value Model		
COA Generation Table	U.S. COA Generation Table / (b)(3):10 U Generation Table		
Bayesian Network	Baseline Bayesian Network	Simplified Bayesian Network (Ordered Likelihoods)	Simplified Bayesian Network (Probability Distributions)
Multiple Objective Decision Analysis	Simplified Value Model (Dominance Analysis)	Baseline MODA Model (Algorithmic Preferences)	Baseline & Simplified MODA Model (Elicited Preferences)

The next section describes the Baseline Bayesian Network for the pilot study. Building on the value measures and COAs, the SME specified the variables and relationships among them.

The Baseline Bayesian network models the situation in which the scenario takes place. Its scope is summarized by the influence diagram. Sets of nodes within the Baseline Bayesian network represent context, U.S. and adversary COAs, and value to the U.S.



A Bayesian network is a graphical representation for a set of random variables and the probabilistic influences among them (Pearl). A random variable is a set of mutually exclusive and exhaustive possible values (outcomes). Nodes of the network represent random variables. Directed arcs of the network represent influences (relationships) among the random variables. The nodes and arcs together constitute the structure of the Bayesian network.

The parameters of a Bayesian network are contained in conditional probability distributions (CPDs) associated with each node. A node's "parents" are those nodes whose arcs point to the node.* Its CPD contains a probability distribution for each combination of the node's parents' outcomes.

The Bayesian network developed with the help of a SME follows these steps:

- Identify relevant random variables
- Define and order the states of the random variables
- Specify the presence of influences among the variables
- Detail the nature of the influence
- Evaluate

* Similarly, the node is called a "child" when it has one or more parents.

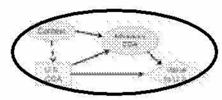
Reference:
Pearl, J. (1988). *Probabilistic Reasoning in Intelligent Systems: Networks of Plausible Inference.* Morgan Kaufmann, San Mateo, CA.

Working with the SME we developed a baseline qualitative Bayesian network

- Built upon
  - The conceptual influence diagram's types of nodes and structure
  - The COAs from the COA generation tables
  - The U.S. value hierarchy and value measures

- Developed sets of nodes for
  - Contextual factors
  - Possible U.S. COAs
  - Possible (b)(5)
  - Value measures assessing U.S. scenario objectives

- Specified dependencies among the nodes



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In a qualitative network, the arrows are annotated indicating the nature of the correlation between a parent and the node of interest: plus for a positive correlation; minus for a negative correlation; neutral for cases when a correlation cannot be specified. In a qualitative network, the influence of specific combinations of states is not specified.

For these correlations to be meaningful, the states of each node must have an implicit order.

- In the case of random variables whose states are numeric, the order is readily apparent.
- For random variables with categorical states (i.e., non-numeric labels), an outside measure provided by the SME may be applied.

Neutral correlations are reserved for the following cases:

- For a node that does not have an order, the correlations between the node and its parents cannot be specified.
- In other cases, even though all nodes have an order, the nature of the correlation may depend upon specific combinations of parents' states and be positive in some cases and negative in others.

Drawing on the U.S. value hierarchy and U.S. and (b)(5) COA generation tables, we developed corresponding COA and value measure variables. We elicited context variables from the SME and specified the relationships and correlations among the variables.

(b)(5)

(b)(5)

(b)(5)

[redacted]

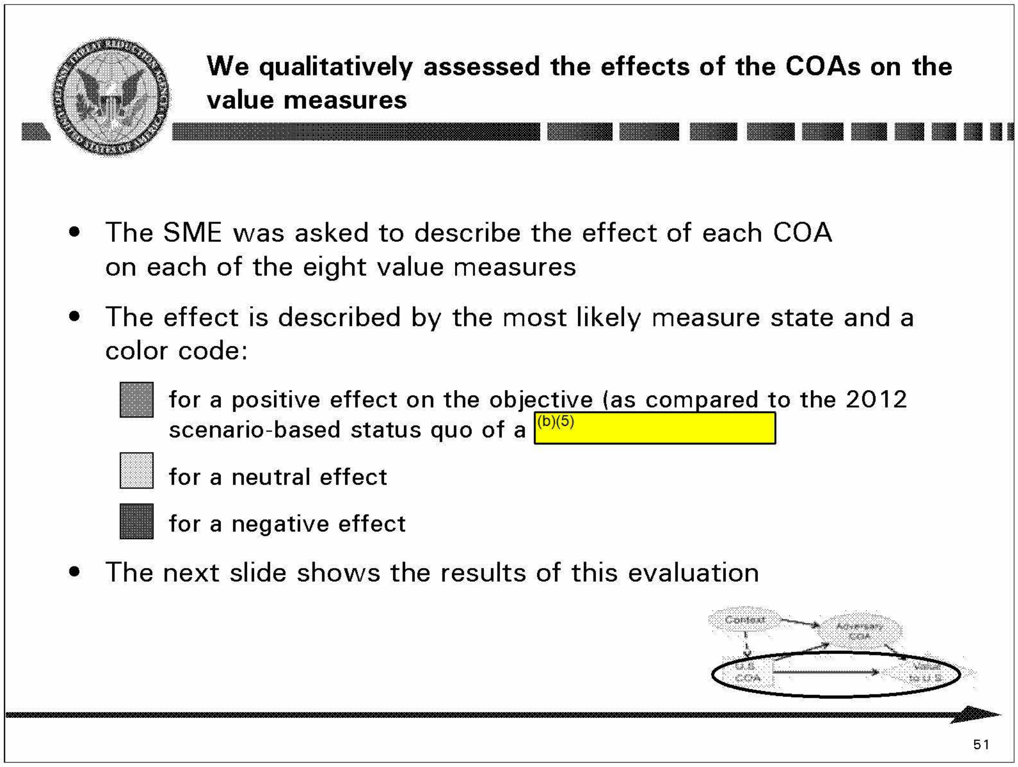
(b)(5)

We developed a qualitative value model

OR Technique	Level of Analysis		
	Qualitative	Semi-Quantitative	Quantitative
Influence Diagram	Conceptual Influence Diagram		
Value-Focused Thinking	Qualitative Value Model		
COA Generation Table	U.S. COA Generation Table / (b)(5) [redacted] COA Generation Table		
Bayesian Network	Baseline Bayesian Network	Simplified Bayesian Network (Ordered Likelihoods)	Simplified Bayesian Network (Probability Distributions)
Multiple Objective Decision Analysis	Simplified Value Model (Dominance Analysis)	Baseline MODA Model (Algorithmic Preferences)	Baseline & Simplified MODA Model (Elicited Preferences)

We next developed a Qualitative Value Model. The SME was asked about the preference order of outcomes.

(b)(5)



The SME was then asked to assess the most likely outcome for each simplified value measure given selection of one of the U.S. COAs developed. “Most likely” refers to the individual outcome state for a value measure that has the highest likelihood of occurring, rather than the median or average state. The U.S. COA was specified, but the (b)(5) [redacted] response COA was not. It was up to the SME to imagine the various (b)(5) [redacted] responses and how they would result in an outcome on each value measure.

The SME actually gave most likely outcomes for all sixteen value measures, but only the eight simplified value measures were used in the qualitative value model.

(b)(5)

We used the MODA technique of dominance analysis to attempt to order the COAs

- A COA dominates another if it is at least as good on all value measures, and is better on at least one
- In the table, if we consider just measure 1, COA A dominates COA B and both dominate COA C
- This is still true if we consider both measure 1 and measure 2
  - COA A dominates B since it is tied on measure 2 but better on measure 1
- If we consider all three measures, COA A now does not dominate any COA, since it is worse than the others on measure 3. COA B does not dominate COA A, since it is worse on measure 1, but it still dominates COA C

COA	Measure 1	Measure 2	Measure 3
COA A	Best	Middle	Middle
COA B	Middle	Middle	Best
COA C	Worst	Worst	Best
Dominates >	Measure 1 A > B > C	Measures 1 and 2 A > B > C	Measures 1, 2 and 3 B > C

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The data from the table on the previous slide was used to perform a dominance analysis to try and identify a partial preference ordering of the COAs.

A COA is said to dominate another if it is at least as good on all value measures, and is better on at least one. This table provides an example of how dominance is identified. In the table, if we consider just measure 1, COA A dominates COA B because its outcome, *Best*, is preferred to COA B's outcome, *Middle*. COA A and COA B both dominate COA C, since it has the worst outcome, *Worst.*

If we simultaneously consider measures A and B we get the same outcome. COA A dominates COA B since it is tied on measure B but better on measure A. COAs A and B both still dominate COA C since C is worse than A and B on both measure 1 and measure 2.

If we consider all three measures, COA A now does not dominate any COA, since it is worse than the others on measure 3. COA B does not dominate COA A, since it is worse on measure 1, but it still dominates COA C.

(b)(5)

"*Take Away*": Qualitative OR techniques show promise for aiding deterrence/influence analysis

- Value-focused thinking
  - Quickly establishes relative priority of U.S. objectives
    - Assessing *adversary's* objectives illuminating in itself...
    - ...while comparing them with U.S. objectives important to identifying likely flashpoints plus potential unanticipated threats
  - Ordered outcomes for value measures quickly identify "hinge events" that can reduce threats posed by adversary
    - E.g., "relinquish nuclear stockpile" removes threat of "nuclear transfer" to others
- Strategy generation table
  - Helpful device for exploratory development of U.S./adversary courses of action across all instruments of national power
  - Encouraged exploration of a wide range of COAs
  - Should be "standard operating procedure" for decision makers, because it provides helpful first-order insights without onerous time burdens

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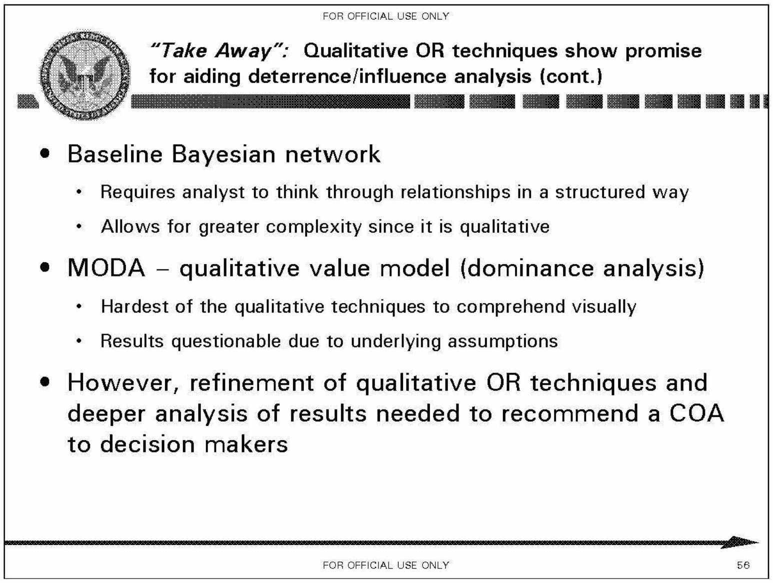
We found that the analysis using the three qualitative operations research techniques (value-focused thinking, COA generation table, and qualitative Bayesian networks) encouraged systematic thinking and provided some useful analytic insights.

The SME was able to provide the data and found the systematic thinking useful. The value hierarchy systematically defined the U.S. and adversary objectives and the range of potential outcomes. The strategy generation tables encouraged exploration of a wide range of COAs. Finally, the qualitative Bayesian network identified relevant context variables and dependencies among variables.

The analysis team believes that the structured information could provide useful data for decisionmakers but that more analysis would be needed to recommend a COA. Furthermore, the qualitative analysis is an essential foundation for the subsequent quantitative analysis.

The SME offered insights on the specific qualitative techniques used, described on the next slide.



The SME offered the following insights on qualitative techniques that are relevant to deterrence analysts, as well as decision makers:

Value-Focused Thinking:

- It enabled an authoritative establishment of U.S. strategic objectives by tracing back to official strategy documents. This framework further permitted an analytical link to be drawn between overall U.S. strategy and scenario-specific objectives. While it is not possible to authoritatively trace back (b)(5) objectives to comparable strategy documents, the analytical process is sufficiently transparent to support SME peer review and refinement.
- The process of applying value-focused thinking to the adversary is also illuminating. In juxtaposing the two, the technique helps identify likely flashpoints between the United States and the adversary, perhaps as well as unanticipated threats.
- Creating value measures for the ordered outcomes helpfully provides an opportunity to quickly establish "hinge events" that, if neutralized, can foreclose a range of undesirable outcomes (e.g., relinquishing one's nuclear stockpile in turn removes the threat of nuclear transfers to others).
- The COA generation table was also a helpful analytical device for quickly developing notional courses of action for both the United States and the adversary, in a manner that touched upon all elements of national power, as opposed to the usual focus on military means.

In short, the SME concluded that value-focused thinking should be "standard operating procedure" for decision makers, not least because it provides helpful first-order insights without imposing onerous time burdens on the user.

Bayesian network:

The qualitative Bayesian network required the SME to identify in a structured manner the relevant context variables and dependencies among variables. Accordingly, the Bayesian network permitted a greater degree of complexity to be modeled.

MODA dominance analysis:

In contrast, the SME found the dominance analysis technique to be less user-friendly, particularly in its visual output. The high ranking of the Regime Change COA was surprising to the SME and raised a cautionary note about the assumptions behind the "most likely" outcome for COAs/simplified value measures.

"Take Away": Qualitative OR techniques show promise for aiding deterrence/influence analysis (cont.)

- Model developer-specific insights:
  - SME understood the analytic framework and readily answered elicitation questions
  - Strategy generation table was easy to develop
    - Built on previous SME work
  - Qualitative Bayesian network
    - Qualitative influences did not provide relative strength of influence
    - Provided only broadest insights, but structuring useful for more quantitative models
  - Qualitative value model
    - Generated only a partial ordering of COAs
    - Structuring useful for more quantitative models
  - Interactions among models
    - Common definitions for COAs and value measure across all models were essential
    - Synergy between the qualitative Bayesian network and the value model improved both
    - We know of no qualitative method to integrate the Bayesian network model results into the qualitative value model

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The pilot study demonstrated the value of integrating a SME into the analytic process of developing the OR models. The SME was prepared to work within the framework of the OR analytic framework and was able to provide the necessary inputs.

We used the COA and value measures generated during the initial steps in both the Qualitative Bayesian Network and the Qualitative Value Model. They became key variables in the Qualitative Bayesian Network. For the Qualitative Value Model, the SME judged outcomes of value measures given particular COAs.

To construct the Qualitative Bayesian Network, we were able to elicit a set of context variables and their possible values from the SME. In that network, the impact of nodes with neutral influence could not be judged without knowing the outcomes of the parent nodes. While a positive (plus) correlation indicates the direction of influence of a parent variable on its child, it cannot tell us to what extent it increases the likelihood of some outcomes over others.

The Qualitative Value Model generated a partial ordering of the COAs. Regime change dominance surprised the SME but reflected his admittedly optimistic assumption for most likely outcomes of Regime Change.

Although we could not directly integrate the Bayesian network with the qualitative model, the elements common to both facilitated their construction and evaluation by the SME.

Report contents

- Background
  - Deterrence campaign framework
  - Notional (b)(5) scenario
- Pilot study – (b)(5) scenario
  - Adversary profile and scenario
  - Overview of methodology
  - Qualitative analysis
  - Semi-quantitative analysis
  - Quantitative analysis
- Results and findings

The semi-quantitative analysis uses algorithms that require little additional judgment from the SME.

We developed a semi-quantitative Bayesian network

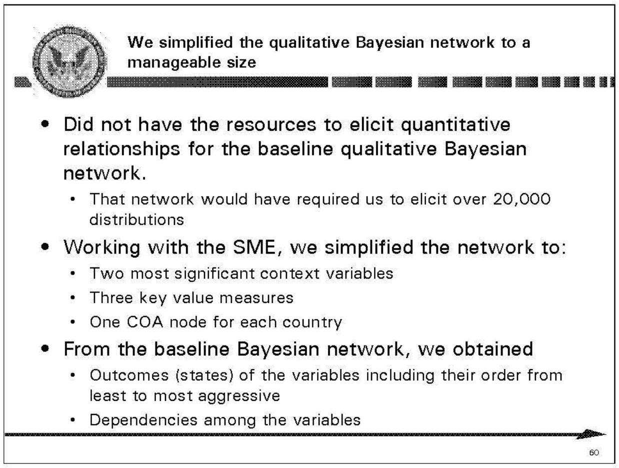
OR Technique	Level of Analysis		
	Qualitative	**Semi-Quantitative**	**Quantitative**
Influence Diagram	Conceptual Influence Diagram		
Value-Focused Thinking	Qualitative Value Model		
COA Generation Table	U.S. COA Generation Table / (b)(5) COA Generation Table		
Bayesian Network	Baseline Bayesian Network	Simplified Bayesian Network (Ordered Likelihoods)	Simplified Bayesian Network (Probability Distributions)
Multiple Objective Decision Analysis	Simplified Value Model (Dominance Analysis)	Baseline MODA Model (Algorithmic Preferences)	Baseline and Simplified MODA Model (Elicited Preferences)

The full Bayesian network provides the structure for modeling the deterrence problem.

Eliciting its parameters, the conditional probability distributions (CPDs), is a challenge because of the large number required. To keep that number to a reasonable size, we reduced the full Bayesian network to a simplified set of variables.

For the semi-quantitative version of the network, we asked the SME to give us orders across the outcomes of each variable. Then, we converted those orders into probability distributions.

This section documents the motivation for reducing the full network to a simplified set of variables, the rationale for the set of variables retained in the simplified network, the approach for eliciting the probability orders, and the algorithms (including their assumptions), used to convert the probability orders to distributions.



Motivation for reducing the full network to a simplified set of variables:

Due to the complexity of the model, we needed to reduce the full network to a simplified set of variables. The structure of the expanded Bayesian network for the scenario has 21 nodes and 48 arcs. Each node has an associated CPD. For each combination of the outcomes of the node's parents, a distribution has to be specified. That network would have required eliciting more than 20,000 distributions.

Working with the SME, we reduced the network to the two most significant context variables, three key value measures, and one COA node for each country.

From the baseline Bayesian network, we obtained outcomes (sometimes called states) of the variables including their order from least to most aggressive towards the U.S., and dependencies among the variables.

(b)(5) [redacted]

We derived the simplified Bayesian network's variables and dependencies from the baseline Bayesian network

- SME determined which variables of the baseline Bayesian network should be retained
  - DIME-specific COA variables were combined into single variables for each country
  - Domestic Politics and Sectarian Strife context variables were retained
  - Value measures for Limit [redacted] Nuclear stockpile, [redacted] WMD Transfer and Defend/Protect U.S. Allies were included
- Dependencies were derived from the baseline Bayesian network by tracing links among the variables
  - An [redacted] COA variable is parent to all three value measure variables in the qualitative Bayesian network
  - Defend/Protect U.S. Allies is indirectly linked to Limit [redacted] Nuclear Stockpile through the [redacted] WMD Use variable in the qualitative Bayesian network and is directly linked to both [redacted] and U.S. COA variables

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Rationale for the set of variables retained in the simplified network:

In the full Bayesian network, each of three COA variables for a country represented one aspect of the DIME actions a country could take. Although the SME believes that [redacted] leadership could follow different COAs at one time (e.g., the diplomatic COA could differ from the military COA), it was deemed reasonable for the purpose of this pilot project to assume a unified COA for [redacted]

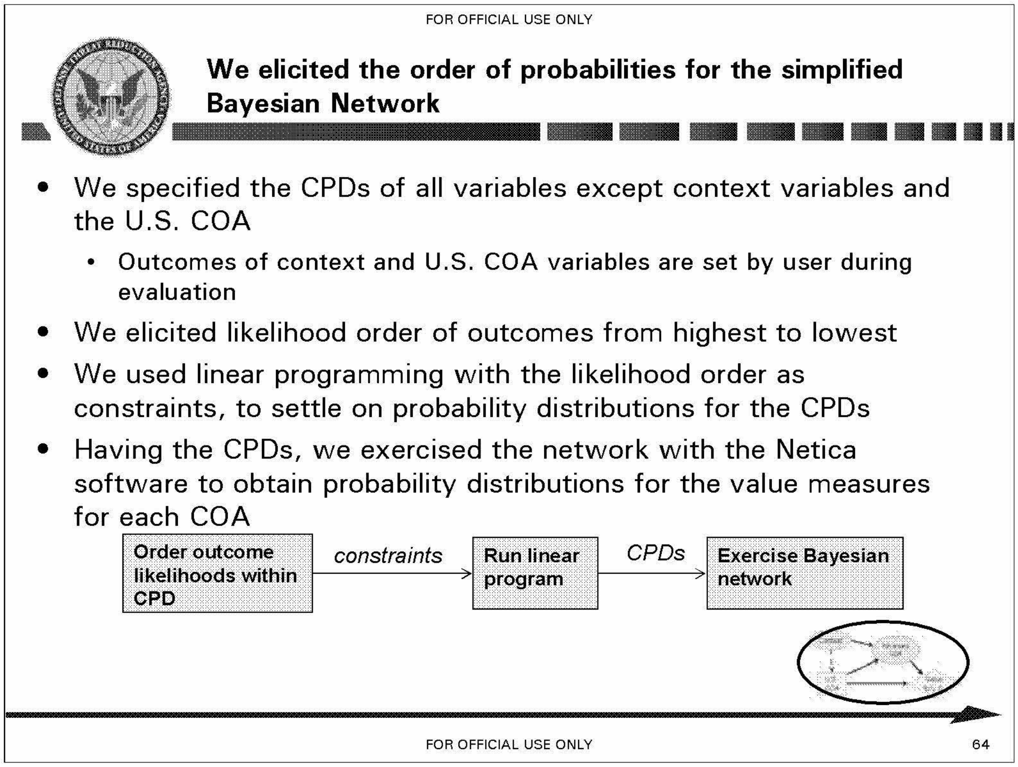
The SME determined that Domestic Politics and [redacted] were the most important context variables for [redacted] COAs.

While the focus on WMD concerns is dictated by the scenario, the SME believed that nuclear weapons-related transfer was more likely, and more dangerous, than direct [redacted] nuclear use and so chose that variable and its precursor, Nuclear Stockpile.

The Defend/Protect U.S. Allies depends on the possibility of Nuclear Use by [redacted] in the full Bayesian network. So nuclear use is understood as a possibility in considering this variable.

(b)(5)

(b)(5)



Approach for eliciting the probability orders:

This slide presents the steps that we used to elicit the likelihood orders for the nodes of the simplified model.

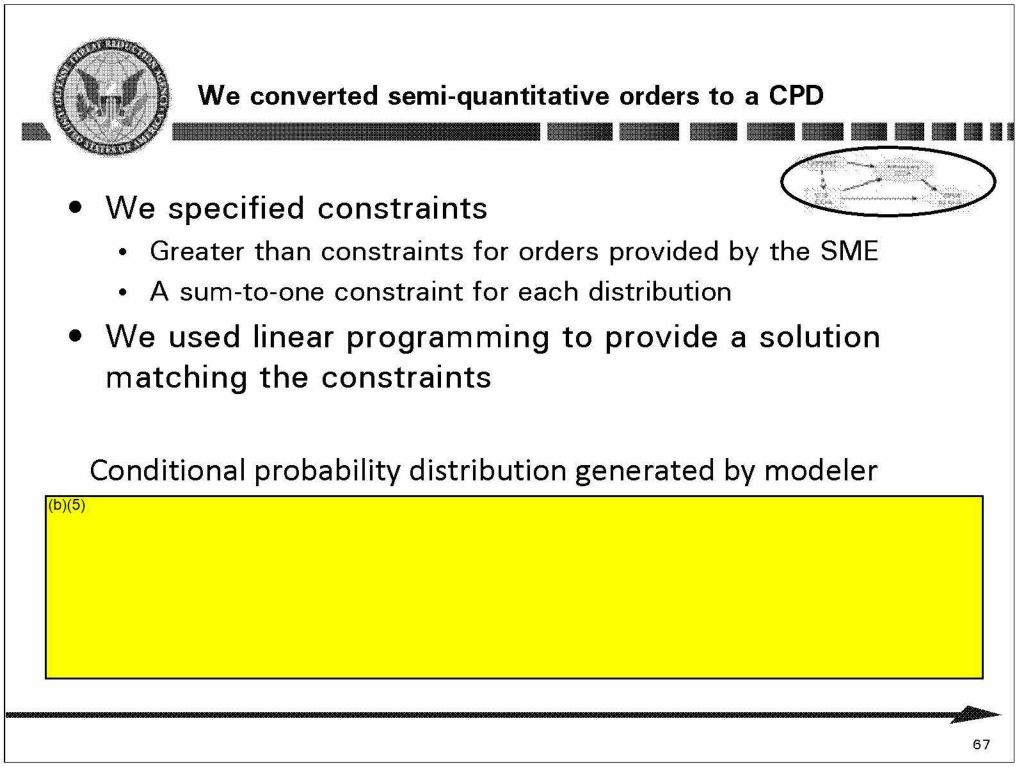
In their experience eliciting probabilities, the authors have noted that SMEs are continually comparing probabilities against one another. SMEs note that one probability is larger than another or that “the odds” are two to one, or that an outcome is more likely under one set of circumstances than another. So, eliciting likelihood orders is not only a possible alternative to eliciting probabilities, it also an approach that SMEs often employ in the process of providing probabilities.

The Netica application that we used to exercise the simplified network does not support eliciting likelihood orders for its random variables. We worked in a spreadsheet to record the likelihood orders and to compute the percentages to be entered into Netica’s application.

The Solver function of Microsoft Excel gives the user the capability to specify constraints for a set of values. The orders provided by the user and the sum to one constraint of probability distributions provided the constraints for Solver.

(b)(5)

(b)(5)



Algorithms, including their assumptions, used to convert the probability orders to distributions

We took the likelihood orders provided and specified constraints. We intentionally required the numbers to be distinct. In other words, in general, we did not allow two numbers associated with a constraint to be identical. For example, a constraint was specified as greater than rather than greater than or equal. This was done primarily to prevent a result in which all the distributions had exactly the same probability for every possibility.

Because we are working with probability distributions, each row is required to sum to 1.0 or 100%.

We took advantage of Excel's Solver function to specify the constraints and compute a set of numbers that meet them.

We also note that there are multiple solutions that satisfy the constraints. The one shown has numbers in "middling" range. We have no additional information to justify one solution over another.

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We developed a semi-quantitative MODA model

OR Technique	Level of Analysis		
	Qualitative	**Semi-Quantitative**	**Quantitative**
Influence Diagram	Conceptual Influence Diagram		
Value-Focused Thinking	Qualitative Value Model		
COA Generation Table	U.S. COA Generation Table / (b)(5) COA Generation Table		
Bayesian Network	Baseline Bayesian Network	Simplified Bayesian Network (Ordered Likelihoods)	Simplified Bayesian Network (Probability Distributions)
Multiple Objective Decision Analysis	Simplified Value Model (Dominance Analysis)	Baseline MODA Model (Algorithmic Preferences)	Baseline and Simplified MODA Model (Elicited Preferences)

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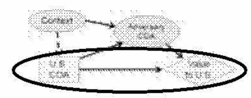
In this section, we show the development of the semi-quantitative version of the MODA model. We required no additional SME input for two reasons. First, the MODA model used the qualitative preference order of outcomes elicited for the Qualitative Value Model. Second, this MODA model used the likelihoods produced by the semi-quantitative simplified Bayesian Network instead of those given by the SME.

We converted the qualitative value model to a semi-quantitative MODA model

- Approach: Use previous qualitative SME judgments and convert them to quantitative estimates using standard algorithms
  - Use the most likely outcomes of the value measures from the qualitative analysis
  - Assume linear value functions across the ordered states (assume equal value increments between states)
  - Use rank order centroid algorithm* to convert qualitative ordering of value measure importance to quantitative weights
  - Assume an additive value model
  - Rank order the COAs using the value model



* See backup charts for details.

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To extend the qualitative value model, we used SME judgments we obtained from the qualitative analysis and converted them to quantitative estimates using standard algorithms. By using this approach, we were able to obtain a complete quantitative ranking of the COAs without having to do any further elicitation from the SME.

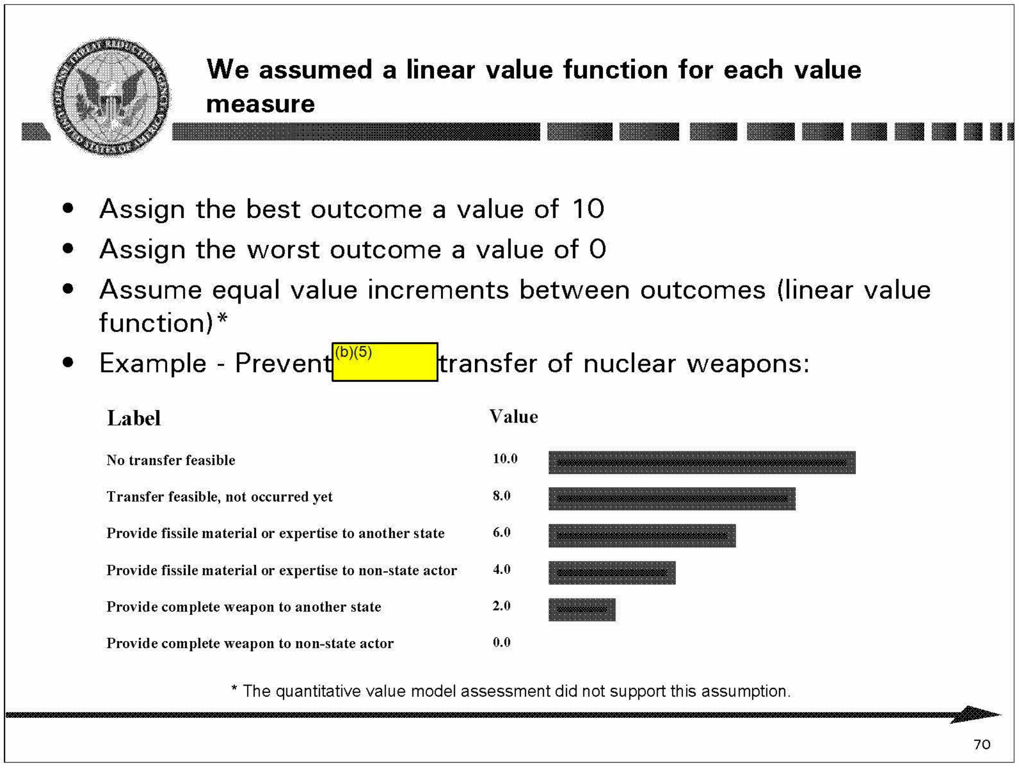
We used the most likely outcomes of the value measures given the COAs that we elicited in the qualitative analysis. No further modification was made to these estimates.

To convert the value measure outcome states to common units of value (a step we did not do in the qualitative analysis), we assume linear value (straight-line) functions across the ordered states. In other words, we assumed that each state represented an equal increment in value from the one below it.

We used an approach called the "rank order centroid algorithm" to convert the qualitative ordering of value measure importances to quantitative weights. This method, which is explained briefly on slide 71 and is described further in the backup slides, converts a rank-ordering to weights without requiring additional information.

Finally, we assume an additive value model of the form V(COA) = W1*V1(COA) + ... + Wn*Vn(COA), where V(COA) is the overall relative value of the COA, Wi is the weight computed for the ith value measure and Vi(COA) is the value of the most likely outcome of the COA on value measure i.

This formula, the algorithms and the judgments elicited from the SME allowed us to rank-order the COAs.



A value function converts outcomes of a value measure to units of value. Since the units are common to all of the value functions, this conversion allows us to combine them to arrive at an overall value for a COA.

Decision theory allows flexibility for the scale we use for the units of value. We chose to use a scale that assigns a value of 10.0 to the most desirable outcome state for each value measure and a value of 0.0 to the least desirable outcome. 0.0 does not represent an absolute level of value here. Rather, it represents the lowest level of desirability we have defined for a particular value measure. In most cases, it would not be difficult to imagine outcomes that are worse than the outcome assigned a value 0.0 on a value measure.

The range of 0.0 to 10.0 defines the value assigned to the most and least desirable outcomes for a value measure. In the quantitative model, we elicit these intermediate values from the SME. However, for the semi-quantitative model, we did not directly elicit numbers from the SME, so we made a simplifying assumption that each improvement in outcome represents an equal improvement in value.

For example, if there are three outcomes defined, we assume that the increase in value of moving from the least desirable outcome to the middle outcome is the same as the increase in value of moving from the middle outcome to the most desirable outcome. For this to be true, the middle outcome must have a value of 5.0. For a measure with two intermediate outcomes, the values would be 3.33 for the lower intermediate outcome and 6.67 for the higher one, and so on for measures with more intermediate outcomes.

Value functions such as these that have equal value increments between adjacent outcomes are called “linear.”

(b)(5)

We computed an overall value for each COA using an additive value model

- For each value measure, the SME provided the most likely outcome for each COA on the constructed scale
- For each value measure i, the outcome was converted to a value V_i (COA) using the measure's value function
  - Assume this value occurs with probability of 1.0
- The V_i (COA) were combined into an overall value using the weight for each measure in an additive value model:
  - $V(COA) = W_1 * V_1 (COA) + \ldots + W_N * V_N (COA)$

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The MODA model combined the information we had collected so far into an overall value for each COA. The SME had provided the most likely outcome for each COA on the constructed scale for each value measure. These most likely outcomes were converted to a value V_i (COA) for each value measure i using the measure's value function. This resulted in a set of values corresponding to each value measure for the COA.

Next, The V_i (COA) values were combined into an overall value using the weight for each measure in an additive value model:

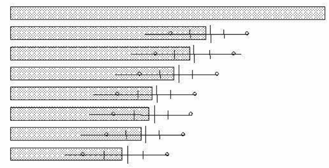
$$V(COA) = W_1 * V_1 (COA) + \ldots + W_N * V_N (COA)$$

The weights were obtained using the rank order centroid method as described on the previous slide. The V(COA) for each COA allowed them to be directly compared. The COA with the highest V(COA) is the most preferred according to the MODA model.

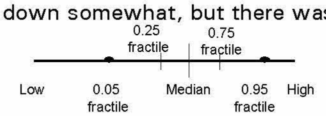
(b)(5)

We updated the semi-quantitative MODA results by incorporating the probabilities for three value measures from the simplified Bayesian network

U.S. COA	Value	Original Value
Ideal	10.0	10.0
Promote cooperative rollback	6.2	7.5
Regime Change	5.7	6.7
Status Quo	5.2	5.4
Deter nuclear transfer	4.5	4.9
Accommodate (b)([redacted]	4.4	4.5
Deter nuclear use	4.2	3.3
Attempt to destroy (b)(5) [redacted] nuclear capability	3.6	3.1



- The uncertainty bars reflect the range of variability from the Bayesian network
- The probability of each state for each value measure and COA was imported into the MODA software from the Bayesian network software and encoded as a discrete distribution
- The error bars were generated using a Monte-Carlo simulation feature built into the MODA software
- The COA values went down somewhat, but there was little change in the rank order



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The semi-quantitative MODA model was modified to incorporate the results of the semi-quantitative Bayesian network. In that network, three of the value measures had their outcomes computed as probability distributions: (b)(5) [redacted] WMD Transfer," "Defend/Protect U.S. Allies" and "Limit (b)(5) [redacted] Nuclear Stockpile."

The probability of each outcome state for each of the three value measures and each COA was imported into the MODA software from the Bayesian network software and encoded as a discrete probability distribution. A probability distribution for each COA's overall value was generated using a Monte Carlo simulation feature built into the MODA software (Logical Decisions, version 6.1). The probability distribution for overall value is computed by conducting a series of Monte Carlo trials. For each trial, each value measure probability distribution is sampled and a particular outcome for that trial is identified. The value of the COA outcome represented by the trial's samples is computed and saved. The probability distribution for a COA reflects how frequently each overall value was observed.

The probability distributions are shown in the graph as uncertainty bars, that indicate the minimum, 95th percentile, 75th percentile, median (50th percentile), 25th percentile, 5th percentile and minimum observed in the distribution, as indicated in the legend to the graph.

When the probability distributions were added, the COA values went down somewhat, as can be seen by comparing with the original values shown on the right, but there was little change in their rank order.

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***"Take Away":* Semi-quantitative OR techniques offer questionable value-added for deterrence/influence analysis**

- Bayesian network – ordered likelihoods
  - The number of nodes had to be downsized to keep process manageable
- Full MODA model – algorithmic preferences
  - Visually, a major improvement over dominance analysis
  - But assumption to use equal value increments is questionable since some increments are significantly worse (see value function on slide 70)
- Combined approach
  - The introduction of uncertainty bars visually helpful and added a healthy dose of analytical caution
  - Given the overlap in these bars, further testing and refinement would be needed to generate needed levels of confidence
    - On part of deterrence analyst and decision maker

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The SME offered the following insights on semi-quantitative techniques that would be relevant to deterrence analysts and decisionmakers:

Bayesian network – ordered likelihoods:

- Populating the conditional probability distributions (CPDs) for the network was a time-consuming process. It can also be perplexing, as one strives to be internally consistent in assigning probabilities across multiple variables. To be practical in light of the project's resource constraints, it was necessary to reduce the full Bayesian net to a subset of the nodes judged to be more critical. In the end, this proved to be a useful prioritization exercise, requiring a down-selection to the most critical nodes in the net.
- If resources had permitted, it would have been helpful to perform a sensitivity analysis on the nodes not included in the simplified net, in effect testing them in a modular fashion (again, to keep the CPD population process manageable). This might have provided higher confidence that, in fact, the most important nodes had been included in the simplified net. More broadly, the population of the CPDs is a natural point for conducting SME peer review.
- Otherwise, it was not possible for the SME to draw a conclusion as to the utility of the Bayesian net at this stage of the project.

MODA model – algorithmic preferences:

- For visual clarity, the algorithmic preference approach was a major improvement over dominance analysis. This also provides another natural focal point for SME peer review.
- Because this stage relied on the SME's previous judgments as to the most likely outcomes, it also replicated problems with the high ranking of the Regime Change COA.

Combined approach:

- The introduction of uncertainty bars added greater detail to the analysis, underscoring for the first time (at least in a readily visible manner) the impact that uncertainty can have on the models. Future efforts would have to delve deeper into the implications of uncertainty in order for deterrence analysts, as well as decisionmaker audiences, to have sufficient confidence in the results.

"Take Away": Semi-quantitative OR techniques offer questionable value-added for deterrence/influence analysis (cont.)

- Model developer-specific insights
  - Bayesian network
    - Demands of elicitation required us to reduce the Bayesian net to its most significant nodes
    - SME found ordering of probabilities for even this highly simplified network a demanding exercise
    - Assumptions used to compute probabilities led to low confidence in the results
  - MODA model
    - Algorithms and assumptions used allowed development of a quantitative MODA model without additional SME input
    - MODA model generated a cardinal COA ranking, but again, the assumptions led to low confidence in the results
      - Equal value function increments was worse assumption that the weighting assumption

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Most significantly, this semi-quantitative exercise illustrates how to integrate the Bayesian network and MODA models.

Based upon orderings given by the SME, we were able to generate quantitative results for both the simplified Bayesian Network and the MODA model. However, because any given order may be converted to an infinite number of possible numeric versions, we had to make assumptions about the relationships among the orders. A common assumption is that the differences between neighboring orders are the same.

In other words, if we first have values 1 and 2, the next value is 3. Note that the numbers 1, 2, and 8 also satisfy the same ordering. Sensitivity analysis could identify most critical assumptions for further SME elicitation.

Interestingly, the COAs that dominated in the qualitative analysis have the greatest values in the semi-quantitative case. But the quantitative results show a large overlap in the values for each alternative. This overlap gives us warning and suggests that further analysis would be required before making any recommendation.

Because of the large numbers of probability orders required, we reduced the size of the Qualitative Bayesian Network before eliciting orders of probabilities from the SME.

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Report contents

- Background
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- Pilot study – nuclear (b)(5) scenario
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  - Semi-quantitative analysis
  - Quantitative analysis
- Results and findings

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Having completed the discussion of the semi-quantitative analysis based on orders elicited from the SME, we next discuss the quantitative analysis, which provides the full analysis with quantitative assessments from the SME.

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We developed a quantitative Bayesian network

OR Technique	Level of Analysis		
	Qualitative	**Semi-Quantitative**	**Quantitative**
Influence Diagram	Conceptual Influence Diagram		
Value-Focused Thinking	Qualitative Value Model		
COA Generation Table	U.S. COA Generation Table / (b)(5) COA Generation Table		
Bayesian Network	Baseline Bayesian Network	Simplified Bayesian Network (Ordered Likelihoods)	Simplified Bayesian Network (Probability Distributions)
Multiple Objective Decision Analysis	Simplified Value Model (Dominance Analysis)	Baseline MODA Model (Algorithmic Preferences)	Baseline and Simplified MODA Model (Elicited Preferences)

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This section describes the quantitative Bayesian Network. We refined the semi-quantitative simplified Bayesian Network by eliciting probability distributions for its CPDs. In this section, we will note the probability distributions that we elicited and describe how they differ from the semi-quantitative network.

We elicited probability distributions to replace those derived from algorithms based on ordinal ranking of outcomes

- During elicitation
  - SME used nodes to refresh his memory about the precise definitions of the variables and their possible outcomes
  - SME referred to orders elicited for probabilities during the development of the semi-quantitative network to populate tables in quantitative network.
- Due to time limitations, SME provided probability distributions for all but one of the variables
  - (b)(5) Courses of Action – 140 distributions (b)(5)
  - WMD Transfer – 20 distributions
  - Limit (b)(5) Nuclear Stockpile – 5 distributio
  - ~~Defend/Protect U.S. Allies – 980 distributions~~

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When we elicited probability distributions for the simplified Bayesian Network, the SME made extensive use of all prior work. This included focusing on the precise definitions of the COAs and value measures. It also entailed referring to orders or probabilities elicited to construct the semi-quantitative version of the network. Thus, while a fully quantitative model requires a great deal of work, the SME leveraged prior qualitative and semi-quantitative work.

Due to time limitations, the SME provided 165 probability distributions for three of the random variables in the simplified Bayesian Network.

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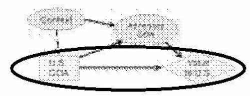
We developed quantitative MODA models

OR Technique	Level of Analysis		
	Qualitative	**Semi-Quantitative**	**Quantitative**
Influence Diagram	Conceptual Influence Diagram		
Value-Focused Thinking	Qualitative Value Model		
COA Generation Table	U.S. COA Generation Table / (b)(5) COA Generation Table		
Bayesian Network	Baseline Bayesian Network	Simplified Bayesian Network (Ordered Likelihoods)	Simplified Bayesian Network (Probability Distributions)
Multiple Objective Decision Analysis	Simplified Value Model (Dominance Analysis)	Baseline MODA Model (Algorithmic Preferences)	Baseline and Simplified MODA Model (Elicited Preferences)

In this section, we construct the Quantitative MODA Model by eliciting value measure weights and outcome values from the SME.

We extended semi-quantitative MODA analysis to a full quantitative analysis

- Used the value measures and most likely states developed for the qualitative analysis
- Incorporated probabilities from simplified quantitative Bayesian network
- Elicited additional SME judgments to obtain quantitative model parameters
  - Value functions
  - Value measure weights



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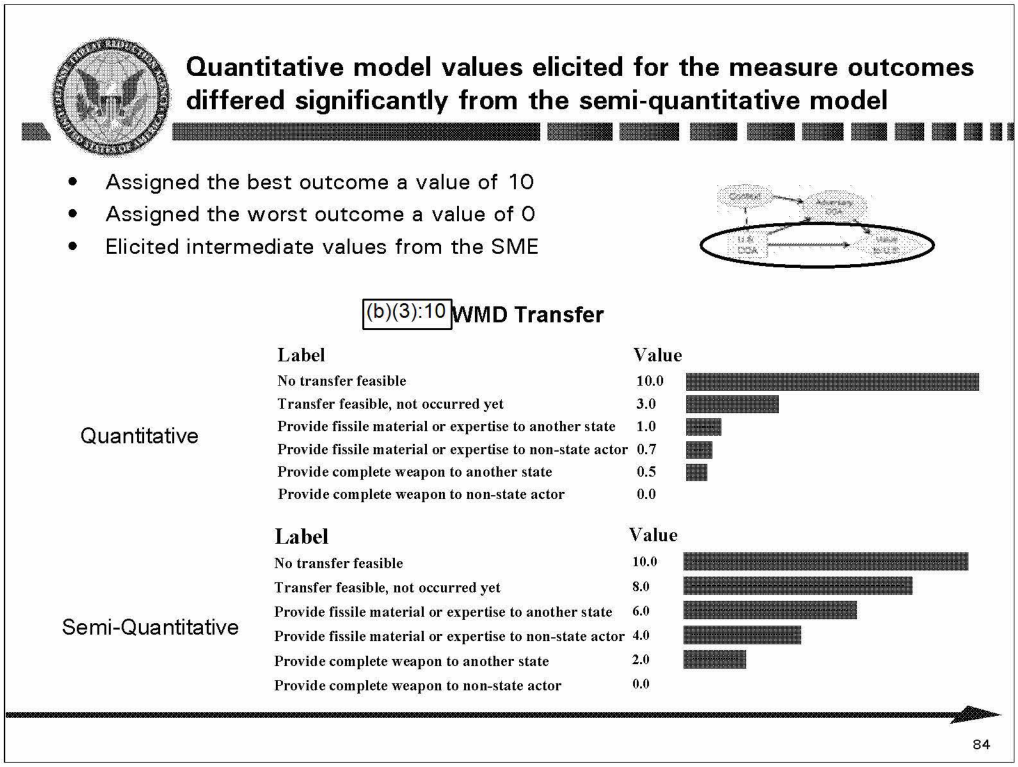
The quantitative MODA analysis extended the qualitative value model and the semi-quantitative MODA model. From the qualitative model, we retained the value measures, their associated scales, and the SME's assessment of the most likely outcome state for each COA and value measure. The weighted additive value model from the semi-qualitative MODA model was retained, but was updated with numerical judgments elicited from the SME.

The probability distributions obtained from the semi-quantitative Bayesian network were replaced by the corresponding probability distributions from the quantitative Bayesian network. The same Monte Carlo simulation procedure that was used in the semi-quantitative MODA model was used here to compute the overall value probability distribution for each COA.

The numerical judgments elicited from the SME included the values corresponding to the intermediate outcome states of the value measures, which were elicited by asking the percentage of the overall value range from the least desirable to the most desirable outcome.

Additional judgments were used to establish the weights for each value measure. The swing-weight matrix technique, which is described in a later slide, was used for the weight elicitation.

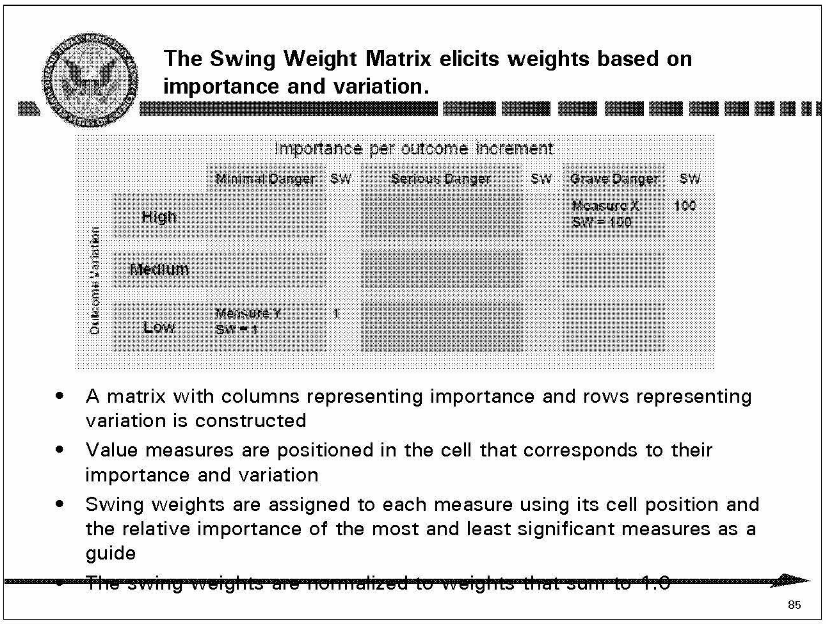
These elicitations allowed us to update the value model from the semi-quantitative MODA model and to use the Logical Decisions MODA software to compute the overall expected utility and probability distribution for each COA.



The same type of value functions were used in the semi-quantitative and quantitative MODA models, with the following difference: instead of assuming an equal increase in value for each outcome state over its predecessor, the SME was asked to directly state the value to be associated with each outcome.

Remember from the discussion of the semi-quantitative value functions that the values of the most and least desirable outcomes were fixed at 10.0 and 0.0 respectively. Thus, the SME was only required to specify values for the intermediate outcomes. We elicited each intermediate value by asking the SME what fraction of the range between the least and most desirable outcomes was represented by the particular outcome under consideration. For example, in the value function for (b)(5) WMD Transfer" shown above, the SME felt that the outcome "Provide fissile material or expertise to another state" represented only 10 percent of the value range from "Provide complete weapon to a non-state actor" to "No transfer feasible." Thus, "Provide fissile material or expertise to another state" was assigned a value of 1.0 on the 0 to 10.0 value range.

As can be seen from the graphs, the shape of the quantitative value function for "(b)(5) WMD Transfer "was quite different from the shape of the semi-quantitative value function. This was because the SME felt that the "No transfer feasible" outcome was much more desirable for the U.S. than any of the other outcomes and that the "Transfer feasible, not occurred yet" state was again much more desirable than the outcomes below it. This indicates that the linear assumption made in the semi-quantitative model was a poor approximation for the SME's elicited value function. This was true for several of the other value measures, as well, including "(b)(5) WMD Use," "(b)(5)" and "Defend/Protect U.S. Allies."



The swing weight matrix method was developed by Dr. Greg Parnell (Trainor and Parnell, in Sage, 2008). An early application was in the 2005 Army Base Realignment and Closure (BRAC) process (Ewing, *et al.,* 2006). Swing weights are elicited based on the concept of the relative importance of "swinging" a value measure's outcome from the least desirable to the most desirable.

$$w_i = SW_i / (\sum_{i=1}^{n} SW_i), \quad SW_i = \text{matrix swing weight corresponding to measure } i.$$

The swing matrix process proceeds as follows:

- First, a matrix with columns representing importance and rows representing variation is constructed. We can think of importance here as being proportional to the average relative significance of improving a value measure outcome to the next most preferred outcome. We can think of variation as being proportional to the number of different outcome states. Clearly, the most important value measures are those with the most significance per outcome increment and the most increments, while the least important value measures are those with the least significance per increment and the fewest increments.
- Once the matrix has been created, each value measure is positioned in the cell that corresponds to its importance and variation. Typically, the most and least important measures as determined by the SME's initial ordering are positioned first and one of them is assigned an arbitrary value, such as 100 for the most important measure. Then the SME judges the relative overall importance by considering the per-unit importance and the number of units. Once the ratio of importance for the two measures has been judged, the swing for the second measure can be computed. In the graphic above, the SME has stated that Measure X has 100 times the importance of measure Y, so if Measure X's swing weight is 100, then Measure Y's must be 1.0.
- The process continues by positioning each measure in the proper cell and then assigning it a swing weight relative to the most important measure. The swing weights can be assigned to the measures directly, or they can be assigned to matrix cells and assigning that weight to each measure positioned in the cell.
- Once a swing weight has been assigned to each value measure, the swing weights are normalized to fractional weights that sum to 1.0 for use in the overall value function.

References:

Ewing, P., Tarantino, W., and Parnell G., "Use of Decision Analysis in the Army Base Realignment and Closure (BRAC) 2005 Military Value Analysis," *Decision Analysis Journal*, Vol 3, No1, March 2006, pp. 33-49.

Trainor, T., and Parnell, G.S., "Problem Definition," in *Decision Making for Systems Engineering and Management,* Wiley Series in Systems Engineering, Andrew P. Sage, Editor, Wiley & Sons Inc., 2008, pp. 263-315.

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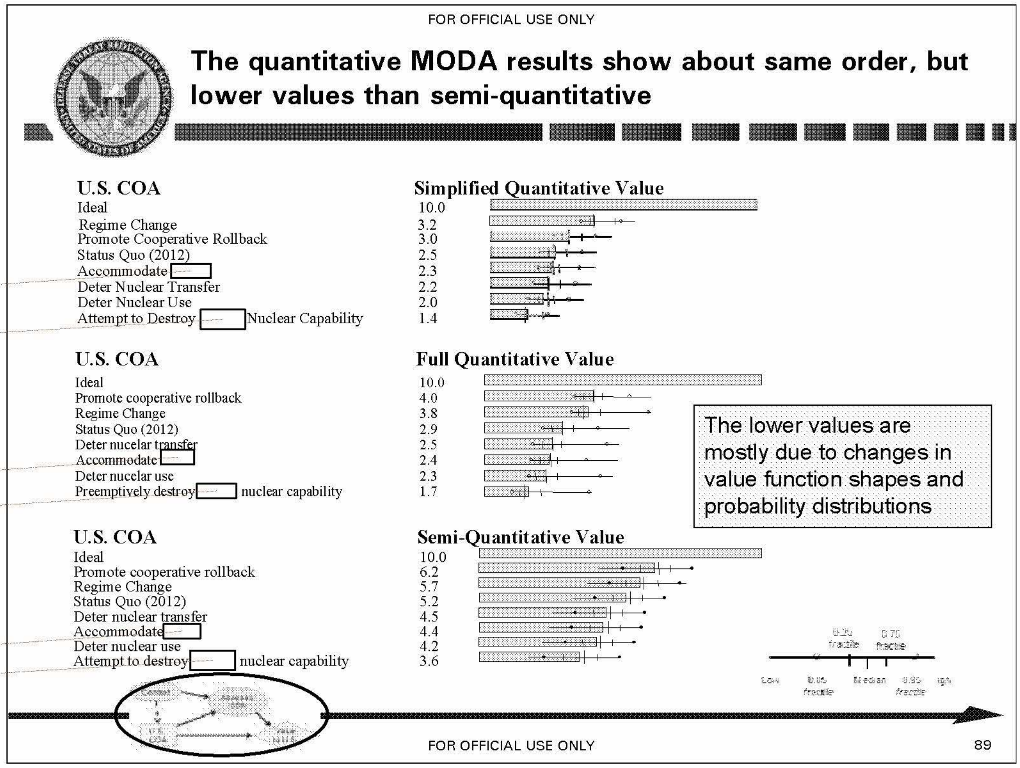

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The full quantitative MODA model shows the same ordering as the semi-quantitative model. However, the values are somewhat lower. This is a consequence of the more extreme value functions in the full model, which tended to lower values for COAs with intermediate outcomes on the value measures. In addition, the probability distributions in the quantitative Bayesian network tended to have more likelihood placed on undesirable outcomes than those of the semi-quantitative Bayesian network.

The simplified quantitative MODA model had lower values and also some shifts in rank ordering from the full quantitative model. “Regime Change” replaces “Promote Cooperative Rollback” as the most preferred COA and “Accommodate (b)(5)” moves above “Deter Nuclear Transfer” in the ordering.

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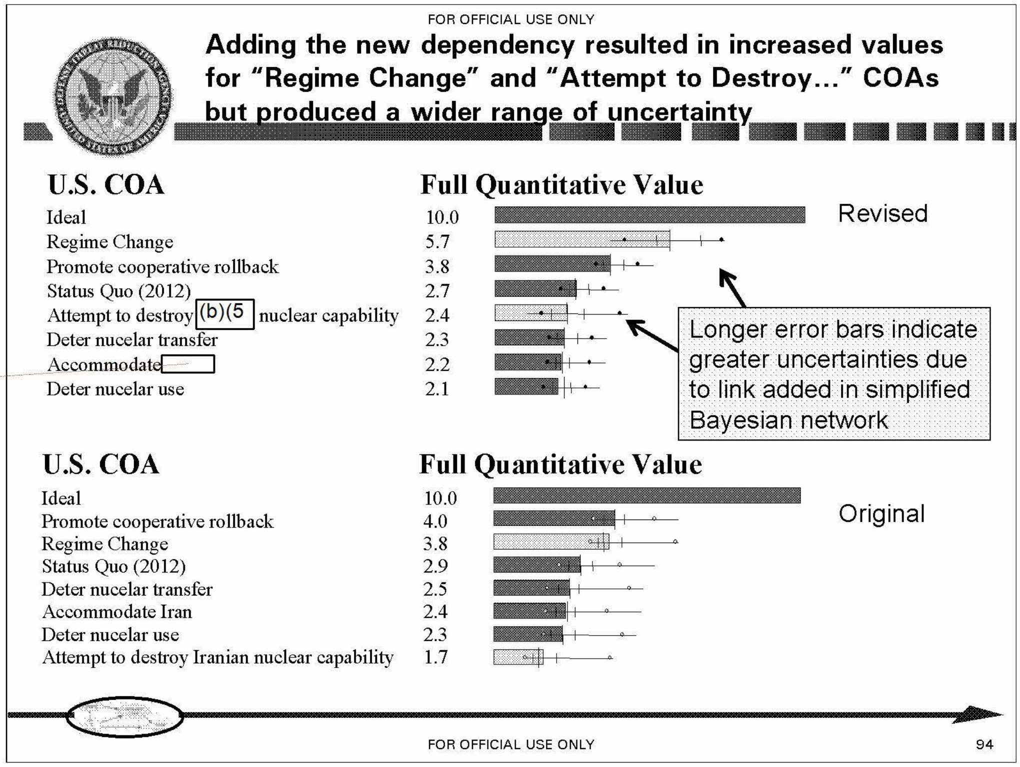

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When the probabilities from the revised Bayesian network were incorporated into the full quantitative MODA model, "Regime Change" became the highest-ranked COA. However, the uncertainty surrounding its overall value increased, as reflected by the longer error bar for the revised result.

The "Attempt to Destroy (b)(5) Nuclear Capability" COA improved from the lowest-ranked COA to the fourth-highest-ranked COA, but its uncertainty also increased.

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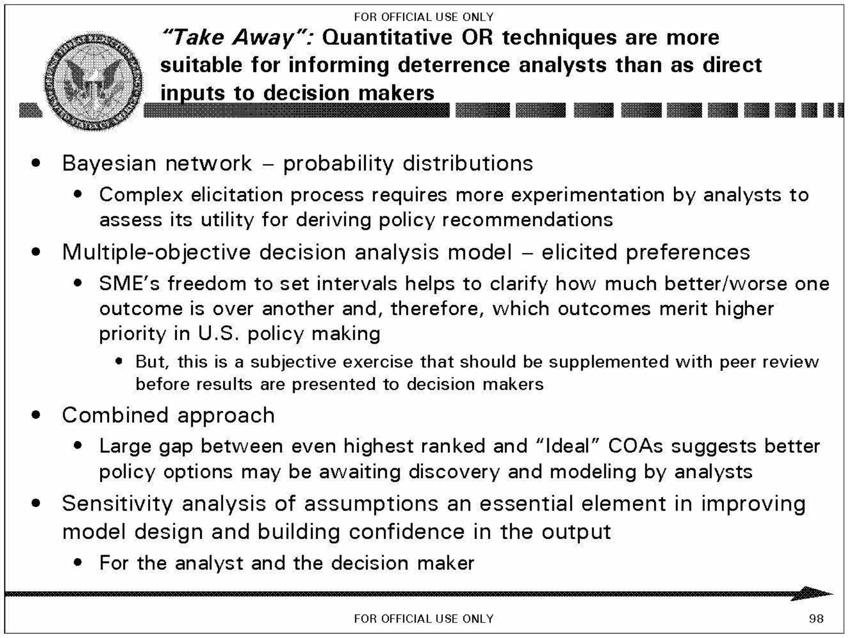

The SME offered the following insights on quantitative techniques that would be relevant to deterrence analysts, as well as decisionmakers:

Bayesian network – probability distributions:

- Shifting from a scale of 1 to 5 with fixed intervals in the semi-quantitative stage to a scale of <1 to 100 with no fixed intervals in the quantitative stage made for a more onerous, although in the end still manageable, elicitation process for the SME. To help manage this process, the SME did "copy" and "paste" some distributions to help populate the tables.
- Being able to refer back to COAs and previously-ordered likelihoods was essential to maintaining a degree of consistency in SME judgments, particularly as the elicitation sessions were spread out over many weeks due to other commitments. This leveraging of previous work was not without its downsides, however, as it risked replicating faulty assumptions.
- Overall, greater opportunities for the team to review output and experiment with the Bayesian network would have enabled the SME to form a more complete opinion as to its utility.

MODA model – elicited preferences:

- The freedom to set the intervals among the outcomes was a more direct expression of SME weighting. It helped the SME to clarify in his own thinking how much better or worse one outcome was in relation to another and, therefore, which outcomes deserved higher priority in U.S. policy making. At the same time, this weighting represented the views of just one SME. To generate greater confidence in the MODA results, SME peer review of this weighting would be in order.

Combined approach:

- Of note to the SME was the gap between even the most promising U.S. COA (under semi-quantitative, full quantitative, or simplified quantitative) and the "Ideal" in this project. This gap may simply reflect an outcome where there are "no good options" for the U.S., given the complex interaction of U.S. and adversary COAs, as well as contextual factors. Alternatively, it may indicate that more "homework" is needed on the part of analysts, i.e., further identification of and experimentation with COAs should be undertaken in order to present a more complete picture of COA performance to decisionmakers.

Sensitivity analysis:

- It is essential to build in time to reflect on the analytical results. This then enables networks to be modified and new results to be generated. It would likely take multiple iterations to build up a deterrence analyst's confidence in the results to the level where they merited presentation to decisionmakers.

"Take Away": Quantitative OR techniques more suitable for informing analysts rather than as direct inputs to decision maker (cont.)

- Model developer-specific insights
  - Bayesian network
    - SME input difficult for baseline Bayesian network probabilities, but simplified model was manageable
    - Results were significantly different from semi-quantitative to quantitative models
  - MODA model
    - SME input relatively easy for MODA model swing weights and value functions
    - Followed trend of semi-quantitative model but with reduced values due to more extreme value functions and probabilities
  - Sensitivity analysis
    - Provided additional insight that led to model improvements
    - Significantly changed results
  - Linked OR models provide an integrated analysis capability
    - Important to model variable interdependencies since they affect results
    - Uncertainty in adversary response resulted in large potential range in COA value
    - Pilot study only used 2 quantitative OR techniques, others may be useful

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The quantitative analysis provided a ranking of the COAs and facilitated sensitivity analysis. In developing the quantitative models, we demonstrated that significant differences could be achieved by moving to a fully quantitative approach and by reviewing and revising earlier results. This was particularly evident in the simplified Bayesian network. Even so, the top two in the ordering of outcomes in the MODA model remained unchanged.

The SME was able to provide the quantitative numbers for probabilities, swing weights and value functions. However, the sheer volume in the case of a Bayesian network's probabilities could be daunting.

There were several findings from this pilot study. First, the team believes that an ongoing, integrated SME/OR team effort is essential. Second, we learned that elicitation of SME judgments for multiple objective preferences was easy. The SME found the elicitation of the full Bayesian network model to be onerous, but the smaller simplified model was manageable. Third, we found that sensitivity analysis was essential to improve model design and performance. In addition, the ability to do quick analysis was useful. Fourth, we were able to link the OR models to provide an integrated analysis capability. We found it important to model variable interdependencies since they impact results. Additionally, uncertainty in adversary response resulted in a large potential range in COA value. The pilot study only used two quantitative OR techniques; others may be useful. The study team believes that the quantitative analyses may be more suitable for informing policy analyst and SME judgments, rather than as direct inputs to decisionmakers.

Report contents

- Background
  - Deterrence campaign framework
  - Notional (b)(5) [redacted] scenario
- Pilot study – nuclear (b)(5) [redacted] scenario
  - Adversary profile and scenario
  - Overview of methodology
  - Qualitative analysis
  - Semi-quantitative analysis
  - Quantitative analysis
- Results and findings

Additional findings follow.

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"Final Take Away": Operations research techniques can enrich deterrence and strategic influence analysis

- Make SME's assumptions and judgments clear and explicit
  - Provide a qualitative analytic structure to identify the important context, value, and decision variables and their interrelationships
  - Enable elicitation of quantitative probability and value judgments
- Can be integrated into a complete analysis process
  - We integrated and leveraged COA generation table, value-focused thinking/multiple-objective decision analysis, and Bayesian networks
  - Other OR techniques (social networks, game theory, system dynamics, process modeling, etc) could also be integrated
- Support sensitivity analysis to identify critical judgments

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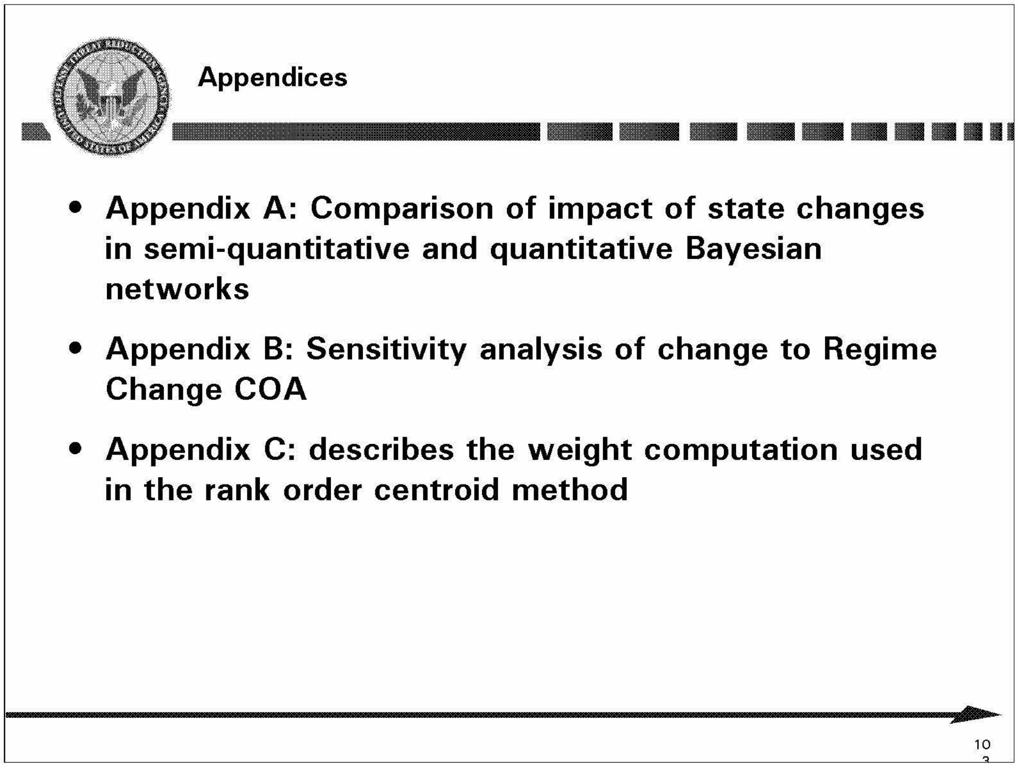
Operations research techniques can enrich deterrence analysis in the following ways.

First, OR techniques make the assumptions and judgments of a SME clear and explicit. They provide a qualitative analytic structure to identify the important context, value, and decision variables and their interrelationships, and they enable elicitation of quantitative probability and value judgments.

Second, OR techniques can be integrated into a complete analysis process. We integrated and leveraged COA generation table, MODA, and Bayesian networks. Other OR techniques (e.g., social networks, game theory, system dynamics, process modeling) could also be integrated into the methodology.

Finally, OR techniques support sensitivity analysis to test critical judgments.



Appendix A shows that changes in states have a greater impact on results nodes in the quantitative Bayesian network than in the semi-quantitative network. This indicates that the semi-quantitative network might understate the effect of different U.S. COAs.

Appendix B explores the SME's interest in examining the effect of a more aggressive response by Iran to attempted regime change.

Appendix C was added to allow the weight computation from the rank order centroid method to be reproduced.

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Appendix B: Sensitivity analysis experiment for "Regime Change" COA

- High ranking of Regime Change COA "surprising" and questionable
  - Risks of WMD use as regime "fights for its life" not adequately considered
- In wrapping up the project, we conducted a mini-sensitivity analysis experiment
  - Changing most likely outcome from "possess but not use WMD" to "nuclear use against U.S. forces in region" makes regime change much less attractive and eliminates its dominance of the other COAs except for deter nuclear use
  - Highlights need for peer review and sensitivity analysis
  - Underscores importance of analytical caveats and assumptions

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The high ranking of the "Regime Change" COA was surprising to the SME and raised an analytical red flag. This can be attributed to the limited scope of the models we developed, which do not consider the full range of political and economic costs. In addition, the pilot study included no analysis of the uncertainties of the relationships among variables. We have no way to ascertain the sensitivity of the outcome of one variable to a change in outcome of another variable. Lastly, we did not review and revise the qualitative models with the SME at a strictly qualitative level. Had we done so, we would have given more consideration to the risk that the (b)(5) regime would resort to WMD use in a fight for its very survival.

Specifically, altering the assumption of most likely outcome from "possess but not use WMD" to "nuclear use against U.S. forces in region" eliminates the dominance of "Regime Change" over the other COAs except for "Deter Nuclear Use."

In short, these results underscore the importance of understanding the underlying analytical assumptions and caveats, as well as building into the process peer review and sensitivity analysis.

Appendix C: The rank order centroid (SMARTER) method

- The SMARTER method is an approach for computing a set of weights based solely on a rank ordering of value measures or objectives
- We start by identifying the most important measure and set its importance as 1
- Then we establish the relative order for the other measures by asking a question like:
  - Improving X from its worst to its best level had the most relative importance. Which measure would you improve from its worst to its best level next.
- Once we have the measures ordered, we compute weights using a geometric method that finds the "centroid" (center of mass) of the extreme possibilities for the weights

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The SMARTER method is the quickest and easiest method from the decisionmaker's perspective. The only judgment needed is an ordering of the measures' importances. All the other methods require at least ratios of importances, a much more difficult task. The drawback, of course, is that the result is only a rough guess of the weights.

Appendix C (cont.): Computing rank order centroid (SMARTER) weights

- SMARTER weights are based on the extreme possibilities given the ordering
- For two measures (A and B), the extremes are:
  - 100% weight on A or 50% weight on A, 50% weight on B
  - The SMARTER weights are the average of these possibilities:
  - 75% weight on A, 25% weight on B
- For three measures, extremes are:
  - 100% A or 50% A, 50% B, or 33% A, 33% B, 33% C
  - The SMARTER weights are the average of the three extremes:
  - 61% A, 28% B, 11% C
- Each additional measure adds another possible extreme point for the weights

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Note that the weights assigned are based on the number of measures being ranked. Every rank ordering of the same number of measures will result in the same set of weights. The system becomes more complicated when ties and minimum weights are allowed.