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Enhancing Assessments of Space Mission Assurance

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Preface

It has become increasingly clear over the past two decades that warfare could extend to space and that space is no longer a benign domain. The national security space community has taken steps to enhance space mission assurance in response. This has led to an increase in demand for assessments of space mission assurance for decision support to acquisition and operations. This report describes decisionmaker needs for space mission assurance assessments, challenges for conducting these assessments, the shortfalls that could result from the challenges, and options for addressing the shortfalls.

This project, titled "A Methodology for Defining a Resilient Space Enterprise in Support of the Joint Force," was sponsored by the Director of Space Programs, Office of the Assistant Secretary of the Air Force for Acquisition (SAF/AQS) and was performed within the Force Modernization and Employment Program of RAND Project AIR FORCE. The research was conducted between October 2017 and August 2018, and this report does not reflect changes beyond those dates. The report should be of interest to Air Force analysts and decisionmakers, the national security space community, and joint force planners.

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Summary

There is an increasing likelihood that future wars will extend to the space domain. This drives an urgent need for space mission assurance (SMA)[1] assessments to support decisionmaking.

Issue

What steps can leadership and analysts in the Department of the U.S. Air Force (USAF) and broader national security space (NSS) community take to enhance analytic methods for assessing SMA? To address this question, we identified decisionmaker needs for SMA assessments, examined analytic methods available to conduct these assessments, and identified the shortfalls in the available methods for meeting those needs. We employed semistructured interviews and literature reviews to inform the analysis. Additionally, the research team examined a selection of models to better understand the capabilities of available analytic methods and to evaluate potential options for addressing the shortfalls. This research was conducted in 2018.

Conclusions

Decisionmakers in the acquisition community need assessments characterizing the value of SMA to inform a range of space investment decisions, such as architecture development, budget decisions, requirements development, and future concept development. These assessments can be used to balance SMA considerations with capability and cost. The operational community needs SMA assessments to support the development of operational plans (OPLANs) and tactics, and to provide decision support for command and control of space operations.

Five existing analytic methods for assessing SMA are identified in this report, and there are advantages and disadvantages to each. The methods and metrics used for SMA assessments need to be selected based on the specific decisionmaker needs, which is the case for similar assessments in other domains. The existing methods lack adequate uncertainty analyses, which are needed to address a shortfall described next.

The shortfalls are not unique to SMA assessments but are more severe than they are for similar assessments in other domains. Factors contributing to the severity include the relative newness of space as a warfighting domain, fragmentation of roles and responsibilities within the NSS community, and challenges associated with compartmentalization of data and information associated with SMA assessments. There are shortfalls (labeled S1 through S4) in

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[1] SMA is defined in Joint Chiefs of Staff, 2018, p. I-7.

- (S1) established baseline and uncertainty bounds for inputs and assumptions needed for SMA assessments
- (S2) available methods for assessing social-behavioral aspects of SMA
- (S3) SMA assessments linking space to terrestrial warfighting operations
- (S4) SMA assessments spanning multiple mission areas.[2]

Recommendations

USAF leadership should undertake the following three recommendations, which will require coordination with leadership across the NSS and may help to address all of the shortfalls:

- Continue to fund and support the efforts undertaken by the Joint Space Warfighting Forum (JSWF), which is currently funded through fiscal year 2020.[3]
- Undertake an initiative to solve challenges associated with information-sharing. Specifically, we recommend establishing security constructs with terms of reference to facilitate the sharing of information.[4] Security classification guides should be reviewed and revised as needed to provide appropriate representation of capabilities at multiple security levels and access channels.
- Establish and fund an SMA Innovation Initiative to accelerate the closing of the shortfalls. A similar approach by U.S. Department of Defense (DoD) senior leaders has contributed to recent progress in wargaming, including establishment of a "Defense Innovation Initiative" by Secretary of Defense Chuck Hagel in 2014, and establishment of an innovation fund to "reinvigorate and expand" efforts across the community by Secretary of Defense Ash Carter in 2016 (Hagel, 2014, and Carter, 2016).

The following additional recommendations for USAF leadership and analysts may help to address specific shortfalls:

- At a minimum, analysts should employ sensitivity analyses to help address shortfall S1. Leadership in the NSS analytic communities needs to ensure that analysts have sufficient resources and scope to employ these methods. For more-complex SMA assessments, sensitivity analyses may be inadequate and more-sophisticated exploratory analysis methods may be needed, which leads us to the next recommendation.
- Employ analytic methods designed for decisionmaking under uncertainty, such as robust decisionmaking (RDM). This recommendation can help to address shortfall S1.
- Characterize the role of space deterrence in SMA assessments and assess corner cases of space deterrence as applicable. Emerging models, such as the Defense Space Analysis

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[2] The numbering of shortfalls does not reflect a prioritization.

[3] We note that subsequent to completion of our research, a Space Analysis Consortium was established in 2018. The purposes of the consortium are the "establishment of a coordinating body, with an accompanying process and battle rhythm, to guide collaborative efforts across the space analytic community. The consortium will address space analytic gaps and needs, and support senior leadership decision-making and national security" (DoD, 2018b, p. 6). This consortium could be the follow-on to the JSWF.

[4] For instance, the Air Dominance Initiative provided a security construct for collaboration and information-sharing by the Defense Advanced Research Projects Agency, USAF, and Navy (McLeary, 2015; Defense Science Board, 2016). Also see Alkire et al., 2018, Appendix D, for historical examples.

Tool and Gaming Investment in Space Technology, may help with assessments of space deterrence. This recommendation helps to address shortfall S2.

- Employ wargaming methods to identify adversary target priorities and rules of engagement regarding space warfare. This recommend can help to address shortfalls S1 and S2.
- Employ campaign outcome–guided mission-level analysis methods to link SMA assessments to operations in other domains and the joint warfight. We illustrate this method in the report. The same approach can also be used to produce SMA assessments that span multiple space mission areas. This recommendation can help to address shortfalls S3 and S4.

Assessing the need for a Space Force and options for implementing it were not within the scope of this project. However, some reports have suggested that reducing fragmentation of the NSS community may be an objective for a Space Force (Hildreth et al., 2018, paragraph 1). Reducing fragmentation could contribute to addressing shortfalls S1 and S4. However, space and air missions are currently integrated within the USAF, so it could be argued that creation of a separate Space Force would increase fragmentation.

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Abbreviations

AADC	area air defense commander
AFSIM	advanced framework for simulation, integration, and modeling
AFSPC	Air Force Space Command
ALR	Aggregate Life Remaining
AoA	analysis of alternatives
ASAT	antisatellite
ASW	antisubmarine warfare
AWACS	Airborne Warning and Control System
BLM	Bureau of Land Management
BMC2	battle management command and control
C2	command and control
CAPE	Cost Assessment and Program Evaluation
CAS	close air support
CDF	cumulative distribution function
CIA	Central Intelligence Agency
COA	course of action
CODE	combat operations in denied environments
COMPOEX	conflict modeling, planning, and outcomes experimentation
CONOPS	concept of operations
DARPA	Defense Advanced Research Projects Agency
DCA	defensive counter air
DIME	diplomatic, information, military and economic
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
DOI	U.S. Department of the Interior
DSC	defensive space control
DSP	Defense Support Program
DSPAT	Defense Space Analysis Tool
EA	electronic attack
FAA	Federal Aviation Administration
FY	fiscal year
GEO	geostationary orbit
GIST	Gaming Investment in Space Technology
GPS	Global Positioning System
HEO	highly elliptical orbit

IAMD	integrated air and missile defense
IC	intelligence community
ISR	intelligence, surveillance, and reconnaissance
JCIDS	Joint Capabilities Integration and Development System
JFACC	joint forces air component commander
JFEO	joint forcible entry operations
JFSCC	Joint Force Space Component Commander
JMEM	Joint Munitions Effectiveness Manual
JSWF	Joint Space Warfighting Forum
KPP	key performance parameter
LEO	low earth orbit
MBSE	model-based systems engineering
MCM	mine countermeasures
MEO	medium earth orbit
MILSATCOM	military satellite communications
MOP	measure of performance
MS&A	modeling, simulation, and analysis
MW	missile warning
NASA	National Air and Space Administration
NB	narrowband
NDAA	National Defense Authorization Act
NNSS	Nevada National Security Site
NORAD	North American Aerospace Defense Command
NRO	National Reconnaissance Office
NSDC	National Space Defense Center
NSS	national security space
NTTR	Nevada Test and Training Range
OCA	offensive counter air
ODNI	Office of the Director of National Intelligence
OORF	on-orbit refueling
OPLAN	operation plan
OSD	Office of the Secretary of Defense
OSC	offensive space control
OUSD(AT&L)	Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics
PDM	program decision memorandum
PDSA	Principal Department of Defense Space Advisor
PK	probability of kill
Pkss	single-shot probability of kill

PM	probability of mitigation
PMESII	political, military, economic, social, information, infrastructure
PNT	position, navigation, and timing
POM	program objective memorandum
PPB	planning, programming, and budgeting
PS	probability of survivability
PSC	protected satellite communication
PTW	protected tactical waveform
RDM	robust decisionmaking
RPA	remotely piloted aircraft
SAC	Strategic Air Command
SAF/AQS	Director of Space Programs, Office of the Assistant Secretary for Acquisition
SATCOM	satellite communications
SBIRS	space-based infrared system
SC	space control
SEAD	suppression of enemy air defenses
SEAS	system effectiveness analysis simulation
SEV	space enterprise vision
SMA	space mission assurance
SOW	state of the world
SSA	space situational awareness
SSDP	Space Security and Defense Program
STAC	Space Threat Assessment Cell
STORM	synthetic theater operations research model
STW	strike warfare
SUW	surface warfare
TBM	theater ballistic missile
TTP	tactics, techniques, and procedures
TVT	threat-vulnerability time line
TWAR	threat warning and response
USAF	U.S. Air Force
USSTRATCOM	U.S. Strategic Command
WB	wideband
WCS	wideband communication services
WSDM	warfighter space dependency model

1. Introduction

Attacks on space systems did not occur in the Cold War because there was no war between major powers, and there was political risk and no obvious benefit to such attacks in peacetime. Today, space is considered a domain of warfare that can be contested (Harrison, 2013). It is increasingly likely that future wars will extend to space.

At the time that our research was conducted (2018), the U.S. government had taken several steps to prepare for a conflict that could extend to space. These steps include the establishment of the National Space Defense Center (NSDC) to "prepare for a fight that extends into space,"[5] and establishment of the Joint Force Space Component Commander (JFSCC) to "help change the collective mindset of space forces from providers of space capabilities to warfighters."[6] In June 2018, President Donald J. Trump directed "the Department of Defense [DoD] and Pentagon to immediately begin the process necessary to establish a Space Force as the sixth branch of the Armed Forces" that is separate from and equal to the other branches (DoD, 2018a, p. 3).

Space mission assurance (SMA) is a concept for mitigating threats to space. Joint doctrine describes three categories of measures to provide for SMA in the following definition:

> **Space Mission Assurance.** Regardless of the threat origin (natural or man-made), there are several methods to provide space mission assurance. These methods can be grouped in three categories of measures: defensive operations, reconstitution, and resilience.[7]

The potential for future wars to extend to space is driving an urgent need for assessments of SMA to provide decision support. Assessments of SMA may be used as decision support for acquisition and operational decisions in the DoD and intelligence community (IC).

Research Questions

The objective of this report is to help the U.S. Air Force (USAF) and the broader national security space (NSS) community[8] enhance analytic methods for assessing SMA. The following four research questions are addressed:

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[5] These remarks are attributed to Gen John Hyten, see Brissett, 2017.

[6] These remarks are attributed to Gen John Raymond, see Air Force Space Command (AFSPC) Public Affairs Office, 2016.

[7] Joint Chiefs of Staff, 2018, p. I-7.

[8] NSS community refers to the interagency collection of space professionals in the services, the IC, the Office of the Secretary of Defense (OSD), the Joint Chiefs of Staff, and the combatant commands. It is unclear how the NSS may reorganize as the United States seeks to establish a Space Force. We also refer to the NSS architecture in this report, which refers to aggregation of DoD and IC space architectures.

1. What are the decisionmaker needs for assessments of SMA?
2. What analytic methods are available to provide the assessments?
3. What are the shortfalls in the available methods to meet those needs?
4. What steps can be taken or what innovations can be adopted to address the shortfalls?

The research did not aim to address all of the challenges associated with defense analyses or to enhance those analyses. Instead, the aim was to narrowly enhance methods for assessing SMA, which appeared to lag behind methods for similar assessments in other domains.

Limitations of the Research

In consultation with the Director of Space Programs, Office of the Assistant Secretary for Acquisition (SAF/AQS), it was determined that emphasis should be placed on the SMA assessment needs of the acquisition community as opposed to the operational community. A key limitation of the research was that researchers had limited access to recent assessments of SMA because of the sensitive and classified nature of those assessments. To help mitigate this limitation, the research team relied on feedback and evaluations of decisionmakers and analysts who had appropriate access.

While space situational awareness (SSA) is a foundational component in the assessment of SMA, a detailed assessment of the needs for SSA products and services to support SMA was outside the scope of this report. Appendix B describes some important gaps.

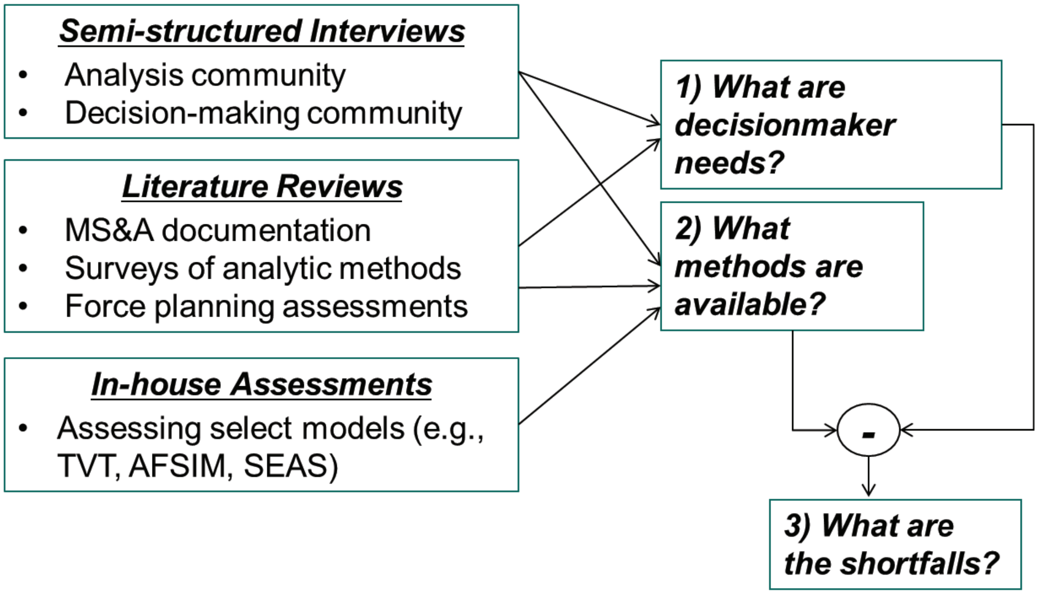
The analytic methods described in this report are suitable for assessing SMA assessments in the context of a two-sided conflict. Given the global nature of space defense, a multiactor analytical framework may be needed.

This research did not focus attention on training needs for analysts.

Methodology

The methodology for answering the first three research questions is depicted in Figure 1.1. It involved semistructured interviews with decisionmakers to identify decisionmaker needs and shortfalls of assessments provided to them in the recent past. Semistructured interviews were also conducted with analysts to identify analytic methods available and to discuss challenges. The research team also relied upon literature reviews for input. Reviews included surveys of analytic models, space decision analyses, and comparisons of SMA assessments to similar analyses conducted for other domains.

Figure 1.1. Methodology for Addressing Research Questions 1 Through 3

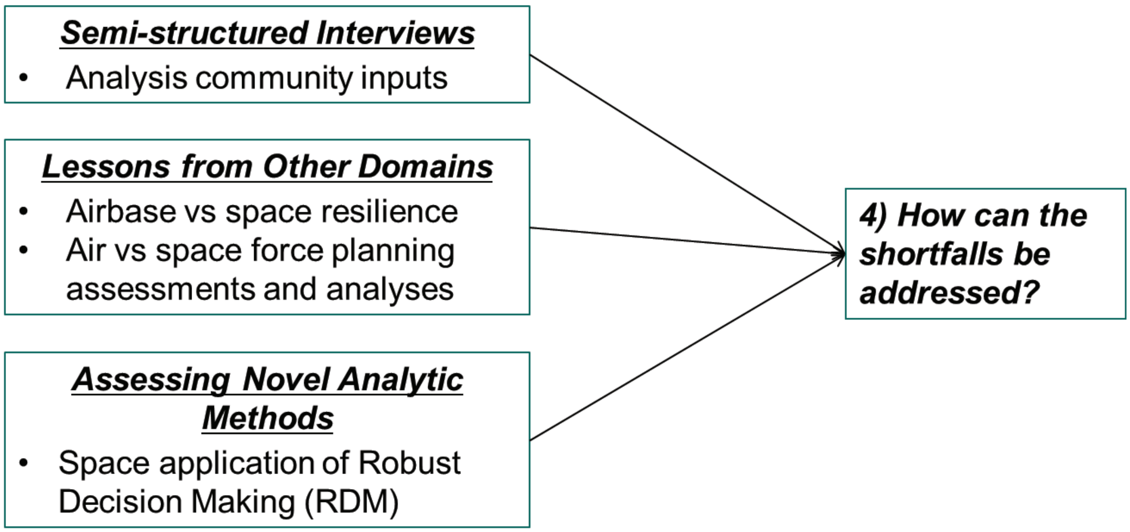


NOTE: Modeling, simulation, and analysis (MS&A); threat-vulnerability time line (TVT); advanced framework for simulation, integration, and modeling (AFSIM); system effectiveness analysis simulation (SEAS).

Figure 1.2 depicts the methodology used to address the fourth and final research question. Semistructured interviews were used to elicit ideas for addressing the shortfalls. Interviews and literature reviews were used to collect lessons from analyses in other domains that could be used to help address shortfalls. The research team examined a selection of models to better understand the capabilities of available analytic methods and their limitations. Also, the research team undertook its own assessments and modeling efforts to evaluate potential steps and innovations that could address the shortfalls. This included in-house development of analytic methods to address shortfalls.

Table 1.1 lists the organizations that provided input for the project. They include the USAF, IC, and joint and interagency organizations.

Figure 1.2. Methodology for Addressing Research Question 4



Report Outline

Chapter 2 describes decisionmaker needs for SMA assessments and addresses the first research question. Chapter 3 describes available methods for SMA assessments and explores the second research question. Chapter 4 describes shortfalls as prescribed by the third research question. Chapter 5 identifies steps the USAF can take to address those shortfalls, thereby answering the fourth and final research question. Chapter 6 provides a summary and conclusions.

Several appendixes are also included, providing additional evidence to support the findings and additional details for implementing the recommendations. Appendix A applies an RDM methodology to a notional SMA assessment for on-orbit refueling.[9] Appendix B summarizes sensitivity analysis with application to SMA assessments, including discussion of limitations. Appendix C applies a campaign outcome–guided mission-level analysis to illustrate how an SMA assessment can be linked to operations in other domains and used to conduct SMA assessments spanning multiple space mission areas. Appendix D describes explicit boundaries for information-sharing that follow from formal classification and need-to-know qualification, and tacit boundaries for information-sharing that arise informally. This appendix also describes examples in which different organizations developed security constructs that facilitated communication of information across tacit boundaries while protecting sensitive details and organizational equities.

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[9] RDM describes several approaches that differ from traditional optimum expected utility analysis, in that these approaches characterize uncertainty with multiple representations of the future rather than a single set of probability distributions and use robustness (rather than optimality) as a decision criterion. See Lempert and Collins, 2007.

Table 1.1. Organizations That Provided Inputs

	USAF	IC	Joint or Interagency
Organizations	• SAF/AQS • Principal Assistant to the Secretary of the Air Force for Space • Principal DoD Space Advisor (PDSA) • Headquarters Air Force/A9 • Air Force Research Lab MS&A working group • AFSPC (A9, A5/8, A2/3/6) • Air Force Warfighting Integration Capability (AFWIC)	• National Reconnaissance Office (NRO) Survivability Assurance Office • NRO Office of Enterprise Analysis • Office of the Director of National Intelligence (ODNI) Space Threat Assessment Cell (STAC) • ODNI Manager Space	• Army Space and Missile Defense Center • Army Training and Doctrine Command • Office of the Under Secretary of Defense for Policy • Office of the Deputy Assistant Secretary of Defense for Space, Strategic, and Intelligence Systems • Joint Staff/J8 • U.S. Strategic Command (USSTRATCOM) NSDC • Cost Assessment and Program Evaluation (CAPE) • Space Security and Defense Program (SSDP) • Joint Space Warfighter Forum (JSWF) • Wideband Communication Services (WCS) Analysis of Alternatives (AoA) Team • Navy N81

2. Decisionmaker Needs for SMA Assessments

The USAF and the broader NSS community are modernizing their space enterprises to address future challenges associated with operating in a contested, denied, and degraded space environment. At the heart of the modernization is enhancing resilience of the space architectures and developing a space force structure that can ensure SMA. To that end, SMA assessments are needed to inform decisions about what a future space enterprise should look like and how to plan and resource accordingly to transform the current space enterprise into the future one. However, our project sponsor was concerned that the current analytic capabilities for SMA assessments are not adequately supporting key investment and force structure decisions.[10] Multiple organizations within NSS have been working toward advancing various elements of analytic capabilities (e.g., model development and analysis process improvements) for improving SMA assessments. Our analysis aims to inform and accelerate those activities.

To gain insights into how the NSS community could enhance SMA assessments, we analyzed decisionmaker needs by examining decision types that require SMA assessments and by eliciting decisionmakers' perspectives on their information needs and shortfalls in past SMA assessments.[11] This chapter describes the information needs (see Chapter 4 for a discussion of shortfalls).

Acquisition Decision Types That Need SMA Assessments

SMA Solution Space for Consideration

There are a wide range of capabilities and approaches that can be considered to enhance SMA. The solution space spans a range of resilience measures, capabilities for defensive operations, and reconstitution capabilities as described in DoD's SMA taxonomy (Figure 2.1).[12] The broad categories of resilience, defensive operations, and reconstitution approaches could be further divided. For example, resilience can comprise six approaches: protection, proliferation, disaggregation, deception, distribution, and diversification. Furthermore, diversification might be

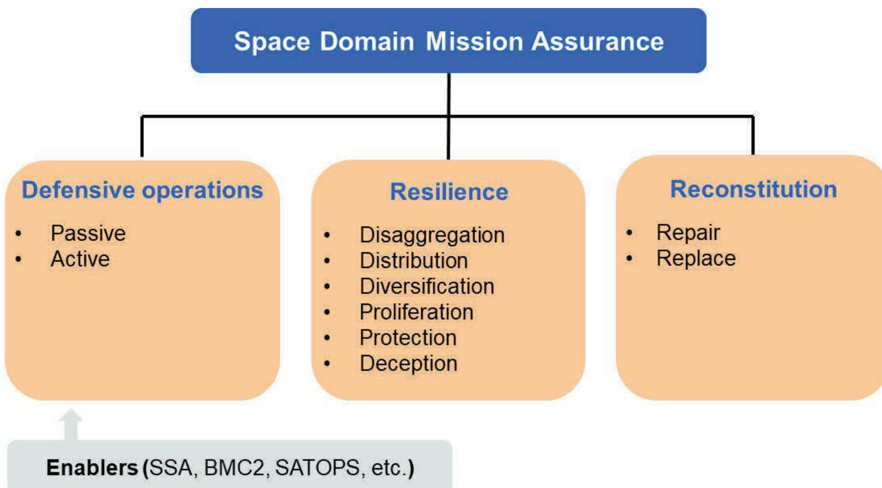
[10] Decisions related to nonmateriel changes to the space enterprise may also need SMA assessments, such as in the planning of operations, strategy, or policy development. However, our research scope is focused on acquisition.

[11] The research team conducted semistructured interviews with personnel in OSD CAPE, the Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics (OUSD[AT&L]), the Office of the Under Secretary of Defense for Policy, the OSD/JS Privacy Office, and AFSPC, whom we considered as representative decisionmakers in the context of our analysis. While assessing past SMA assessments would have provided useful insights, the research team was unable to gain access to those analytic products because of security constraints.

[12] We emphasize the importance of providing decisionmakers with good sets of metrics informed by models, even if qualitative.

further divided into different means of diversification, such as via diverse orbits (low earth orbit [LEO], medium earth orbit [MEO], highly elliptical orbit [HEO], geostationary orbit [GEO], etc.) or diverse providers (commercial, allied, civil, military, etc.). Active defense operations might be divided into self-defense, point defense, or area defense. Note that resilience is an internal attribute of an architecture, while reconstitution and defensive operations focus on attributes or capabilities external to an architecture. Additionally, there are enablers, such as SSA capabilities, that support defensive operations.

Figure 2.1. Elements That Contribute to Space Mission Assurance



SOURCE: Office of the Assistant Secretary of Defense for Homeland Defense and Global Security, 2015, and RAND research.
NOTES: *Space Domain Mission Assurance* and *SMA* are used interchangeably in the literature.
Arguably, SSA should be treated separately, because it enables many of the other enablers.
BMC2 = battle management command and control; SATOPS = satellite operations.

Understanding Decision Types and Their Contexts

Decisions are taking place and will continue to identify, evaluate, and prioritize a range of SMA alternatives for various NSS architectures with contracted commercial and civil space architecture segments. We identified four broad categories of decision types that require SMA assessments, based on our discussions with decisionmakers in the acquisition community. The categories include

- future capability concept development
- architecture and force structure development
- planning, programming, and budgeting (PPB)
- requirements development.[13]

[13] There may be other decision types that require SMA analysis support, but we judged that these four are the key decisions that drive acquisition. Past SMA analyses primarily focused on assessing resilience in support of an AoA

Each decision type presents a different decision problem and different decision contexts, and thus drives the type of analytic capabilities needed for SMA assessments. We describe the SMA-related objectives associated with each decision type and provide example SMA-related questions that may arise in these decisionmaking processes in Table 2.1.

Future capability concept development activities involve identification, evaluation, and prioritization of a set of viable options that enhance SMA, typically in the context of a particular space capability area (e.g., within a protected SATCOM capability area). For example, future concept development to enhance SATCOM mission assurance may involve evaluation of a wide range of SMA options, such as satellite maneuvering capability, protected tactical waveform (PTW), or LEO broadband commercial services.

Table 2.1. Decision Types and Example SMA-Related Questions

Decision Type	SMA-Related Decision Objective	Example SMA-Related Questions to Support Decision
Future capability concept development	• Identify and prioritize a set of viable options to enhance SMA (e.g., development planning)	• How does on-orbit servicing capability enhance SMA? • What are promising threat warning and response (TWAR) technologies that can improve platform survivability? • How does leveraging LEO commercial SATCOM enhance SMA? • How does disaggregation enhance space resilience for strategic missile warning?
Architecture and force structure development	• Determine space architectures and force structures that can meet SMA needs (e.g., SEV architecture development, AoAs)	• Which resilience measure (disaggregation, diversification, proliferation, protection, etc.) or mix of resilience measures yields the most cost-effective, resilient architecture? • What is the right mix of distribution across commercial, allied, and DoD capabilities? • What is the right mix of active and passive defensive operations to meet SMA needs? • Which space mission is suitable for reconstitution? • What is the right level of SSA to support defensive operations?
Planning, programming, and budgeting	• Prioritize investments for short, medium, and long terms to enhance SMA (e.g., planning choices, POM development, evaluation, and defense)	• How should investments be balanced across resilience, defensive operations, and reconstitution capabilities and their enablers? • Which capability enhances resilience the most for the enterprise? • What is the risk to MILSATCOM mission assurance if PTW is not funded?
Requirements development	• Determine SMA requirements • Review, prioritize, and trade SMA requirements	• What is the required level of SMA for SATCOM? • Against which threat(s) should SATCOM be resilient? • Which requirements are higher priority—SSA or SMA for PNT?

NOTE: SEV = space enterprise vision; MILSATCOM = military SATCOM; PNT = position, navigation, and timing.

(e.g., space-based infrared system (SBIRS) follow-on AoA, protected satellite communications (SATCOM) AoA, or wideband (WB) AoA), program objective memorandum (POM) development, issue papers, strategic portfolio reviews, architecture development, requirement trades, and other ad hoc questions (e.g., a National Defense Authorization Act (NDAA)-directed task). Going forward, the USAF and NSS have plans to evaluate defensive operations and reconstitution concepts (AFSPC, 2018).

Furthermore, a range of viable architectural options that include various SMA enhancement approaches could be considered for each space mission area. For example, one SATCOM architecture alternative could be an architecture with disaggregated strategic and tactical communications satellites in GEO, while another one could be an architecture that consists of a few satellites in GEO for strategic communications and proliferated LEO commercial satellites for tactical communications. Many additional architectures employing a range of resilience measures could be considered (see Figure 2.1). Similar architectural evaluations would be conducted for other space capability areas, such as missile warning and PNT.

In force structure decisions, a range of force structure alternatives might be considered for providing SMA in an enterprise context. An alternative could be a set of resilient space architectures with minimal passive defensive operation capabilities. Or it could be a set of space architectures that are resilient to reversible attacks and accompanied by a robust set of passive and active defensive capabilities and reconstitution capabilities for irreversible attacks. Again, a wide range of variations could be considered (see Table 2.1).

SMA assessments are needed in these activities to evaluate the value or benefits of viable SMA alternatives and to support a set of decisions that will ideally lead to an integrated approach to enhancing SMA for the enterprise. These decisions in capability concept, architecture, and force structure development activities are intricately tied together and will be an iterative process. Multiple trades need to be made at different levels during this iterative decision process.

Within DoD, the above activities will influence both the resourcing decisions through the PPB processes and requirements decisions through the joint capabilities integration and development system (JCIDS) process. Decisionmakers need to determine priorities about which set of SMA enhancements (or any of the SMA enhancements) to invest in and budget for during the PPB processes. Setting such priorities becomes increasingly complex as the PPB inputs go through a series of trade-offs and reviews by a diverse set of stakeholders at the AFSPC level, the Headquarters Air Force level, and OSD-level. At AFSPC, investment trades may involve prioritizing among all space mission areas and various SMA enhancements (e.g., SMA for missile warning, SMA for SATCOM, reconstitution capabilities, defensive capabilities, enhanced SSA, or on-orbit servicing capabilities).[14] At the Headquarters Air Force level, decisionmakers may need to prioritize across air, space, or cyber investments (e.g., trade-offs between additional remotely piloted aircraft [RPA] for intelligence, surveillance, and reconnaissance [ISR] and SMA enhancements for SATCOM). At the OSD-level, decisionmakers may need to make trade-offs across services' priorities. Throughout the process, decisionmakers need analytic support to prioritize their SMA investment choices against a range of other investment options.

[14] AFSPC is the USAF's core functional lead for space.

Understanding Warfighter Dependence

The requirements community also needs analytic support for determining and prioritizing SMA requirements. Interviewees have articulated that defining SMA requirements is challenging because of the lack of understanding of warfighter dependence on space. That is, what is the minimum space capability that the warfighter needs to achieve campaign objectives? SMA assessments are needed to evaluate operational risks associated with degraded or lost space capabilities and to make trade-offs about which space capability should be protected, against which threats, and for how long. For instance, if an SMA assessment revealed that enhancing SMA for PNT to counter jamming (vice spoofing or kinetic threats) was adequate to achieve campaign objectives with acceptable risks, that assessment would inform SMA requirements for PNT (recognizing that this is a simplistic example for illustrative purpose only). Or if an analysis highlighted that the lack of assured PNT created a higher operational risk than the lack of assured SATCOM, SMA requirements for PNT could be justified as a higher priority (again, this is a simplistic example for illustrative purposes). SMA assessments may also be needed to determine key performance parameters (KPPs) associated with SMA requirements (e.g., maneuverability KPP).

In addition to the type of decision being supported, there are other factors that affect the decision context and hence the analytic capabilities needed for SMA assessments. For illustrative purposes, we list a few of these factors that might affect the SMA assessments supporting force structure and investment decisions, as follows:

- **Time horizon.** Decisions about longer-term capability development and investments may involve a much broader trade space to consider such factors as potential changes in technology and commercial space opportunities in the long term, as well as second-generation threats.
- **Decisionmaking approach.** Each decisionmaker may have a different approach to prioritizing and balancing investment options. For instance, some decisionmakers might want to know which SMA alternative is robust under a wide range of threats and attack vectors. Other decisionmakers might value an SMA alternative that is optimized to be effective against a few critical, high-priority threats or attack vectors. Certain decisionmakers might value an alternative that provides the most SMA enhancements that can fit within a budget. The risks associated with each choice would likely differ, and understanding such risks would assist the diverse stakeholders in making trade-offs among the alternatives.
- **Decision constraints.** Such factors as existing or legacy architectures; precommitted decisions; or phasing of capability deployment can further constrain the trade space or courses of action (COAs).
- **Decision scope.** Many decisions that require SMA analysis support are not necessarily schedule-driven or part of a deliberate process. There are questions or decisions that demand SMA analyses in an ad hoc manner, such as a tasking from USAF or OSD senior leadership or Congress. Issue papers that come about during the POM development cycle

are also ad hoc. Thus, the decision problem could have a narrow context and be focused on a few specific COAs to be considered.

Providing adequate decision support for SMA assessments would require a good understanding of the decision problem and context. Each SMA assessment may need to be tailored to the decision being supported. That said, there are common analytic needs across these decision types to help decisionmakers evaluate various COAs and conduct trade space analyses. In the next section, we discuss these analytic needs from the decisionmakers' perspectives.

Role of SMA Assessments for the Operational Community

While the emphasis of this research is on SMA assessments for decision support to the acquisition community, the research did identify roles for SMA assessments for decision support to the operational community. The research team visited the NSDC to learn about its needs (NSDC, 2018), and conducted semistructured interviews with force planners to learn about representation of space capabilities and capacities in operation plans (OPLANs) as compared with the representation of capabilities and capacities in other warfighting domains.

Decisionmakers in the operational community have similar needs for SMA assessments, though many of the needs for the operational community are still evolving. SMA assessments can provide decision support to the development of OPLANs and tactics. Operational-level command and control (C2) and BMC2 of defensive space operations will likely need assessments of SMA that are similar to those needed for decision support to acquisition, and the recently established NSDC is acquiring tools to support C2 and BMC2. For instance, the NSDC may need assessments of SMA to develop and maintain the critical asset list and the defended asset list.

Summary

Acquisition decisionmakers desire decision support analyses that could enable a holistic risk discussion among diverse stakeholders when making trade-offs in capability development, PPB, and requirements development activities. They need to understand the value of SMA (preferably tied to warfighting effects) and the trade space among cost, capability, and SMA. They desire transparency, sufficient vetting of analyses, and common understanding of assumptions. SMA assessments with these attributes enable the diverse decisionmaker community to explore and understand the SMA drivers and risks of various COAs. Decisionmakers in the operational community need SMA assessments to inform the development of OPLANs and tactics, and to support operational-level C2 and BMC2.

A robust set of analytic capabilities is likely needed to support a wide range of decision problems in multiple decision contexts. A clear understanding of the specific decision context may be necessary early on in the decision process to ensure that the supporting SMA assessment adequately meets decisionmaker needs. We next turn to examining existing analytic capabilities for SMA assessments in Chapter 3.

3. Existing Analytic Methods

Analytic Methods Currently Used for SMA Assessments

This project did not survey computer models for space assessments, because recent surveys of models are readily available (Bialek, 2017). Instead, we examined analytic methods used for SMA assessments, and we define an *analytic method* as the collection of metrics, models, and data combined with the processes for employing them together to produce an assessment.

We examined analytic methods used in recent SMA assessments. We present five analytic methods that are representative of the methods we examined. We illustrate each method through figures and graphs and discuss their advantages and limitations. As we will discuss again later, it is possible to adopt features from one analytic method to another, which could alter the advantages and limitations. We do not attempt to describe every possible combination of features or to optimize their selection. Instead, we describe the analytic methods and their features based on actual applications.

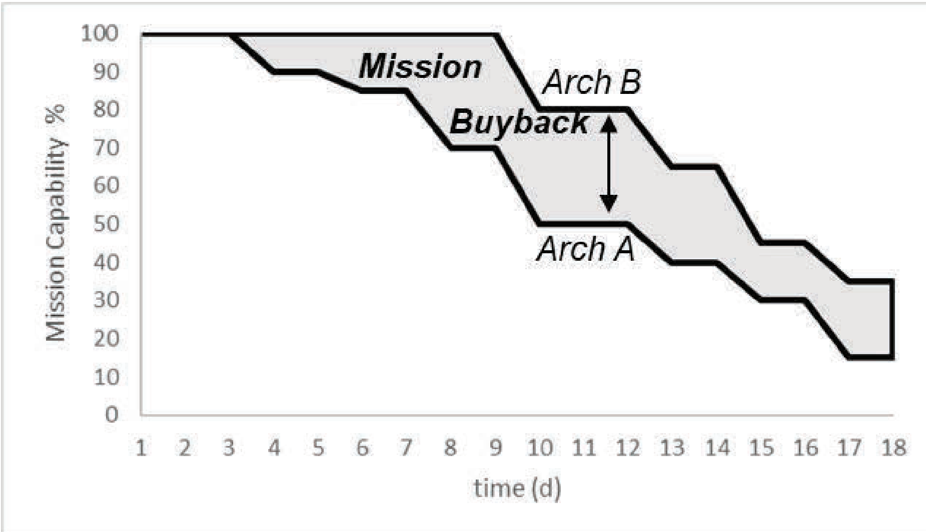
Method 1: Tactical Drawdown

This method involves calculating the system's mission capability during a conflict. Mission capability is measured differently depending on the mission, but one example is the number of relevant images delivered per hour. A sample output of a notional analysis is shown in Figure 3.1. The (notional) time scale in Figure 3.1 ranges from one to 18 days, representing a relatively short (i.e., tactical) time scale (for the space mission being considered). Note the relative performance comparison between the two architectures considered (labeled A and B) and the "mission buyback" illustrated in the figure. The mission buyback value is intended to articulate the incremental performance advantage provided by a given architecture over another. It does not involve or consider any costs, financial or otherwise, associated with the architectures.

Output from Method

The output provided by this method is flexible and customized to the actual mission being assessed. For image delivery, for example, the output could involve the number of images being delivered per hour. Other parameters can include revisit period of a given area, size of coverage area, or communications capacity in a region. One of the benefits of this output is the ease with which different architectures can be compared, as shown in Figure 3.1.

Figure 3.1. Tactical Drawdown Method



Types of Tools Used

The types of tools used depend on the actual mission being assessed and the type of threats being used by Red. The applications we evaluated employed a combination of physics-based engagement and mission-level tools.[15] As an example, for a scenario in which a kinetic antisatellite (ASAT) system is used, a physics-based engagement model would estimate the ability of the ASAT system to intercept the satellite while defeating potential countermeasures deployed against it. The mission-level calculations would then estimate the impact of the ASAT intercept(s) on the overall capability of the constellation to provide the needed imagery, the impact on the area it can cover, or the communication capacity of the system.

Key Inputs and Assumptions

The major inputs to the calculations include Red's order of battle, concept of operations (CONOPS), C2, and weapons capabilities, as well as Blue's weapon-system characteristics, including possible countermeasures (i.e., mitigative actions it can take to defeat the attack). In the application we evaluated, analysts assumed that Red intended to draw down Blue's capability as fast as possible and therefore provides a worst-case condition for Blue.

Advantages

The resulting metric, mission capability, is an easily understandable parameter that does not require any space expertise. The metric is also flexible because it can apply to different missions and provides a measure that is relative to the baseline or nominal performance, as well as applicable among different architectural options.

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[15] We do not mean to imply that physics-based models are limited to the engagement level.

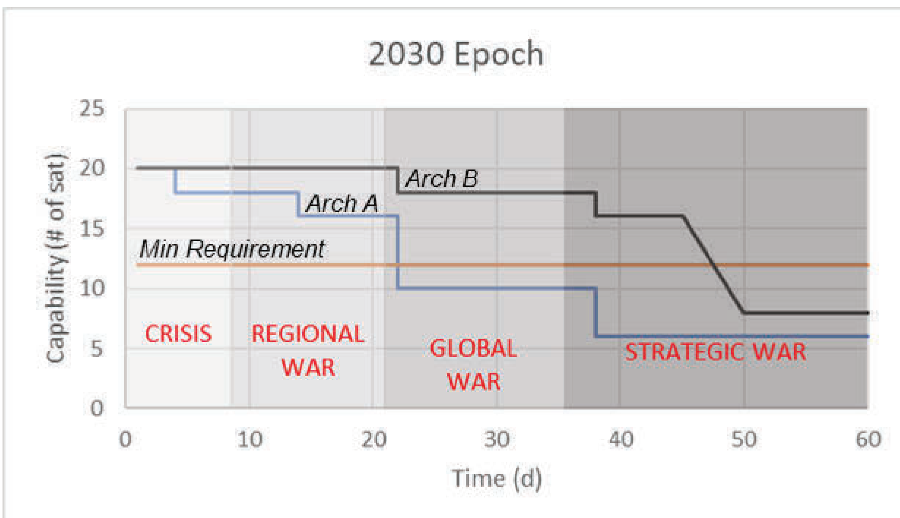
Limitations

The principal limitation is the assumption that Red intends to draw down Blue's space capability as fast as possible. In other words, the method uses a simple CONOPS involving Red attempting an intercept at every opportunity. Another limitation is the lack of cross-domain effects, e.g., potential terrestrial operations to limit Red's capabilities to continue its attacks on Blue systems. The impact of losing the space capability on a joint operation is also not assessed.

Method 2: Operational Drawdown

This method has been used to address an NDAA request related to the resilience of the space architectures. A sample output of a notional analysis is shown in Figure 3.2. It uses a measure of performance similar to the tactical drawdown method.

Figure 3.2. Operational Drawdown Method



Output from Method

The notional results from this approach provide a relative comparison of various constellation capabilities, in terms of the number of remaining satellites, over the different phases of a conflict that range from crisis to strategic war. Additionally, Figure 3.2 includes a measure of the required capability (assumed constant) needed to meet the users' minimum needs, i.e., a measure of degraded performance.

Types of Tools Used

The types of tools needed depend on the offensive weapons being used. However, we assess that physics-based engagement models are needed to do the analysis. As an example, for a scenario in which a notional on-orbit ASAT system is used, the model would estimate the ability of the ASAT system to intercept the satellite while defeating potential countermeasures that could be deployed against it. The engagement would be executed at times specified by the scenario and the types of weapons used by Red might change as the scenario evolves and the conflict escalates.

Key Inputs and Assumptions

The major inputs to the calculations include Red's order of battle, CONOPS, C2, and weapons capabilities, as well as Blue's weapon-system characteristics, including possible countermeasures. Assumptions regarding escalation dynamics by both Red and Blue also need to be made in this approach. The tactical and operational drawdown methods are quite similar, with both showing a drawdown in capability over time. The key differences are the inputs and assumptions used. The tactical drawdown assumes adversary intent is to draw down a space architecture as quickly as possible. In contrast, the operational drawdown method simulates a fictional scenario that evolves from a crisis to a strategic war; adversary intentions are much more complex and varied, and many more assumptions must be made for the operational drawdown method than for the tactical drawdown method.

Advantages

The resulting metric, the capability based on number of satellites, is an easily understandable parameter that does not require any space expertise. The approach also includes an escalation model and calculates the degradation of space capabilities as a function of the phase of conflict. The latter capability can provide a realistic assessment of Blue drawdown over an operational scenario and provides a phase-based assessment of remaining capabilities (e.g., Blue would not expect a full-out attack on its space forces during the initial phase of a conflict because a controlled escalation approach is used).

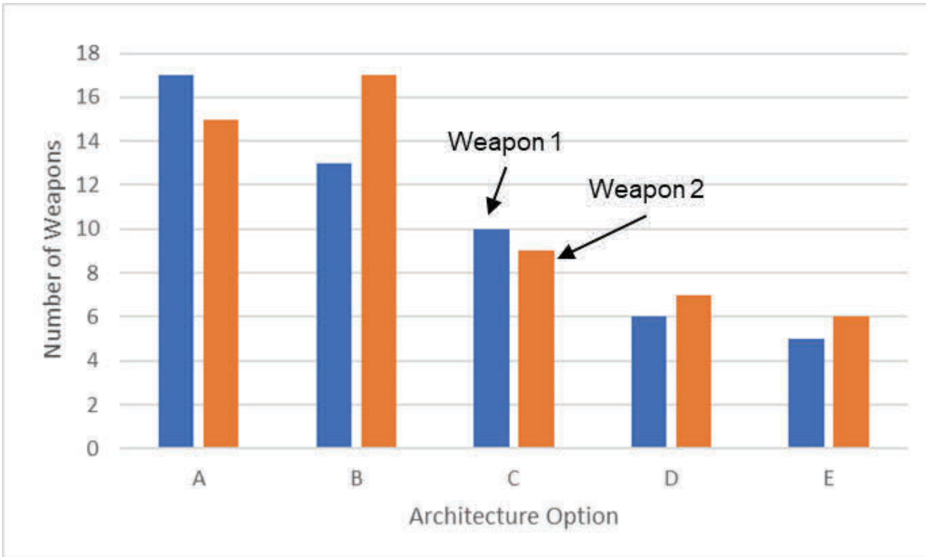
Limitations

The approach requires a number of assumptions regarding conflict escalation by both Red and Blue. Additionally, cross-domain effects and the effects of the architecture degradation on the joint warfight are not considered.

Method 3: Static Force Structure Comparison

Another method used in an AoA that RAND researchers supported involves estimating the ability of various Blue space-force structures to survive attacks by Red counterspace-force structures (OUSD[AT&L], 2013). The approach involved identifying candidate Blue space architectures and simulating Red attacks with different weapons. The output provides a comparison of the space architecture resilience by estimating the number of weapons Red would need to expend to eliminate Blue's space capability (for the specific mission being assessed). A sample output of a notional analysis is shown in Figure 3.3. Note that this approach does not require a scenario, it essentially assesses the survivability of various space architectures versus Red weapons.

Figure 3.3. Static Force Structure Comparison Method



Output from Method

The output provided by this metric is straightforward in that it simply illustrates the number of weapons that Red needs to expend to directly destroy Blue's space assets related to the mission being considered. The output in Figure 3.3 captures two types of weapons; however, any number and type of weapons can be considered. The time needed to destroy the assets is not provided.

Types of Tools Used

The types of tools needed depend on the offensive weapons being used. However, we assess that physics-based engagement tools are needed to do the analysis. As an example, for a scenario in which a direct ascent ASAT system is used, the model would estimate the ability of the ASAT system to intercept the satellite while defeating potential countermeasures that could be deployed against it.

Key Inputs and Assumptions

The major inputs to the calculations include Red's order of battle, CONOPS, C2, and weapons capabilities, as well as Blue's weapon system characteristics, including possible countermeasures. The approach assumes Red has a sufficient number of weapons to directly destroy Blue's space capabilities being assessed.

Advantages

The resulting metric, the number of Red weapons needed, is an easily understandable parameter that does not require any space expertise. The metric is also valuable because it captures the cost to Red and provides insight into the capability of Red to destroy the constellation by considering Red's capacity provided in its order of battle. We note, however, that Red may respond to Blue's resilient architecture by developing additional capacity or capabilities (or both).

Limitations

The principal limitation associated with this method is the assumption that Red intends to completely destroy Blue's space capability associated with the mission being assessed. Another limitation is the lack of cross-domain effects (e.g., potential terrestrial operations to limit Red's capabilities to continue its attacks on Blue systems). Also, the effects of Blue's space system degradation on the joint warfight is not captured.

Method 4: Threat-Vulnerability Time Line

A method currently being used by various DoD organizations is the TVT methodology. TVT was developed by the staff at the PDSA and is being used by AF/A9 and AFSPC, and it is also endorsed by OSD CAPE (Stanton and Zondervan, 2017).[16] The approach provides a flexible method to estimate a measure of performance over both an engagement period and constellation fielding, or reconstitution, cycle. A sample output of a notional analysis is shown in Figure 3.4. The flexibility of this approach allows for the use of simple to complex scenarios as captured by the attributes assigned to specific space nodes, i.e., probability of kill (PK) and probability of mitigation (PM) for each node over the epochs considered. The approach essentially assesses the survivability, and resulting performance, of various space architectures versus Red weapons at periods of interest. We note again that the evolution of both Red and Blue capabilities over the assessed time period can be accounted for in TVT (as captured by varying PK and PM for a constellation at different epochs). For example, Figure 3.4 shows the degradation for a notional constellation in both the engagement time line and the fielding cycle. The vertical axis shows elapsed hours in an engagement, while the horizontal axis shows the year in which the engagement may occur. The values within the heat map represent the number of on-orbit assets surviving or replenished.

[16] Interviews with staff at Headquarters Air Force Studies, Analysis, and Assessments, October 18, 2017.

Figure 3.4. Threat-Vulnerability Time Line

	YEAR					
HOUR	2018	2021	2024	2027	2030	2032
0	11.00	11.00	11.00	11.00	11.00	11.00
5	11.00	11.00	11.00	11.00	11.00	11.00
10	11.00	11.00	11.00	11.00	11.00	11.00
15	11.00	11.00	11.00	11.00	11.00	11.00
20	11.00	11.00	11.00	10.00	11.00	11.00
25	11.00	11.00	10.00	10.00	10.00	11.00
30	11.00	11.00	10.00	10.00	10.00	10.00
35	11.00	11.00	[illegible]	9.00	10.00	10.00
40	11.00	11.00	[illegible]	9.00	10.00	10.00
45	11.00	11.00	10.00	[illegible]	9.00	10.00
50	11.00	11.00	10.00	[illegible]	9.00	10.00
55	11.00	11.00	10.00	8.00	8.00	10.00
60	11.00	11.00	10.00	8.00	8.00	10.00
65	11.00	11.00	10.00	8.00	8.00	10.00
70	11.00	11.00	[illegible]	[illegible]	8.00	10.00
75	11.00	11.00	10.00	8.00	8.00	10.00
80	11.00	11.00	10.00	8.00	8.00	10.00

Decreasing Capability

Notional Example
Measure of Interest: Expected number of operating satellites

Output from Method

The output provided by this approach is customizable to the question being posed. The framework provides the ability to output any measure of performance (MOP) that can be modeled and calculated. The MOP is provided over both an engagement time line (hours to days) and a fielding cycle (many years). A sample output, in the form of a heat map, is given in Figure 3.4.[17] Each cell in the plot represents the performance of the architecture at a specific engagement time during different epochs.

Types of Tools Used

The TVT methodology is based on a statistical approach estimating the probability of survivability (PS). The approach accounts for space-system interdependencies but is low fidelity and directly uses the input values (PK and PM) to estimate survivability and resulting constellation performance. Furthermore, when assessing the resilience of a capability, the constellation performances before and after the engagement can be compared to evaluate multiple and diverse architectures.

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[17] A heat map in this context provides a color-coded performance in which green marks the best performance and red marks the worst.

Key Inputs and Assumptions

The major inputs to the calculations include Red's weapon effectiveness, as captured by PK, and Blue's ability to mitigate the threat, as given by PM. The approach models the engagement outcome by estimating PS from PK and PM by using the following equation (see Stanton, 2017, for details):[18]

$$P_S = \prod_{\tau=1}^{n_T} \left(1 - [P_k]_\tau \left(\prod_{\mu=1}^{n_M} 1 - [P_m]_{\tau,\mu} \right) \right)$$

where

- P_s = the probability of survivability
- P_k = the probability of kill
- P_m = the probability of mitigating the attack
- n_T = the number of threats
- n_M = the number of mitigation factors.

Advantages

The resulting metric, architecture performance, is provided for both a short time line (a specific engagement) and a long time line (a constellation fielding cycle). This approach provides decisionmakers with a view into the operational performance of the architecture for both the short and longer terms. The interdependencies between various space missions is also captured, e.g., weather satellite dependence on SATCOM. These interdependencies provide a more realistic and comprehensive view of a space mission capability. For example, the effect on a user who does not receive the space-based data, such as weather, is the same whether the failure is due to the weather satellite itself or the SATCOM system used to relay the data. Finally, TVT runs very quickly because of the simplicity of the underlying equations. As a result, speed of analysis is an advantage for this method.

Limitations

The principal limitation associated with this approach is the relative simplicity of the performance calculation (the PS). Although the PK and PM can be based on higher-fidelity models, they are used independently and are estimated separately. We note, however, that the framework represented by TVT could be integrated with higher-fidelity models, such as by using the models to calculate PS directly, to improve the resolution of the results. The effect of the space missions on the joint warfight is also not assessed in TVT. Implicit in this approach is a prerequisite that the analysts have at their disposal a model of the architecture or capability to be assessed.

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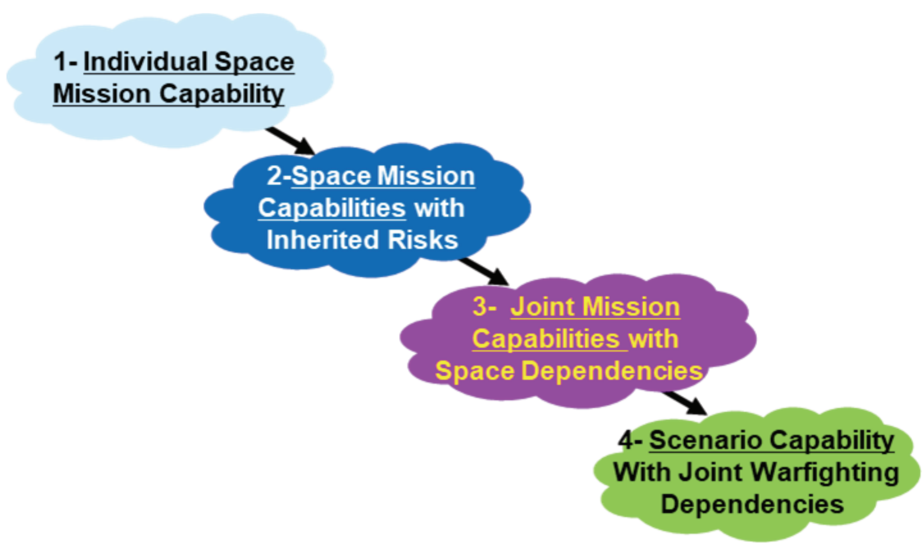
[18] Observe that these equations imply that the threats and mitigation factors can be adequately modeled as independent probabilities.

Method 5: Warfighter Space Dependency Model

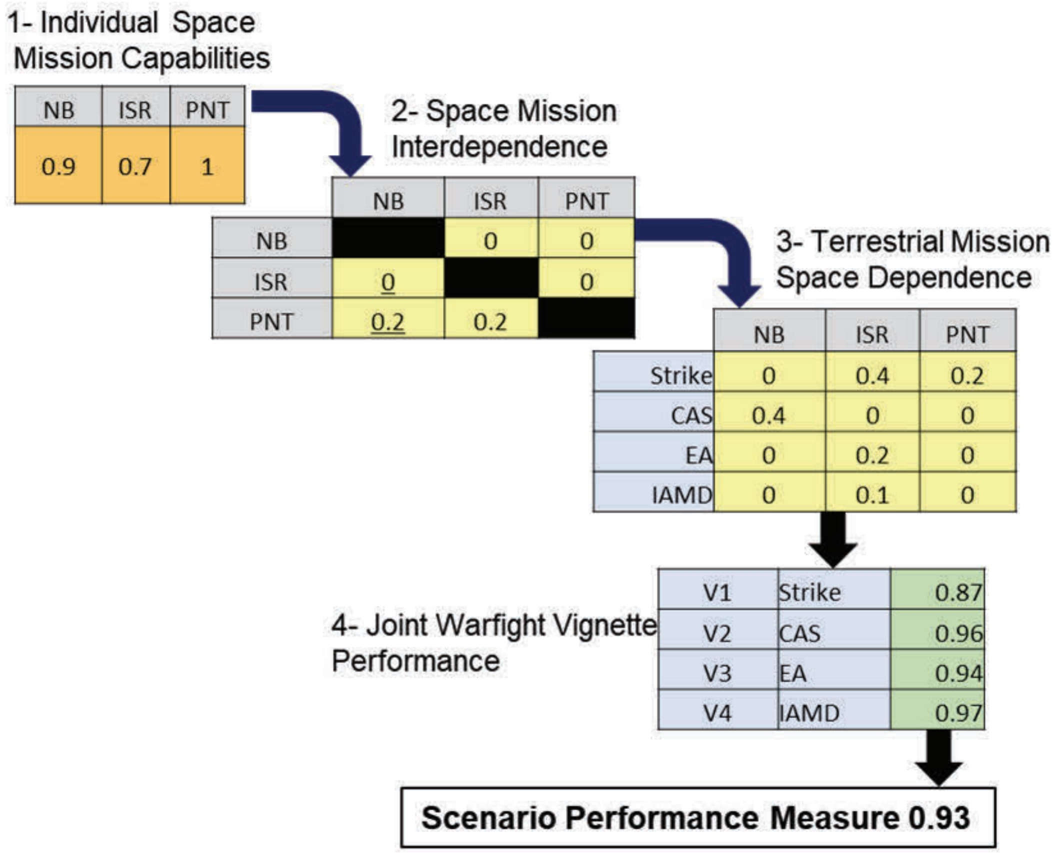
Another analytical tool used by some DoD organizations is the warfighter space dependency model (WSDM) (Stanton, 2017). WSDM was developed by a coalition called the Joint Space Warfighting Forum (JSWF), led by U.S. Strategic Command (USSTRATCOM)/J8 and including the staff at the PDSA. The tool is being used by AF/A9 and USSTRATCOM. The model assesses the impact of the space domain on joint warfighting capabilities and is essentially an extension of TVT. It accounts for the interdependencies between space systems as well as the level of reliance of terrestrial operations and weapon systems on the various space missions. The latter is estimated qualitatively by subject-matter experts and captured in a relational matrix used to estimate the impact of space capabilities on terrestrial mission performance.[19] The WSDM general approach is depicted in Figure 3.5, and Figure 3.6 illustrates the calculation steps involved in WSDM along with the output given in the final step: the Joint Warfight Vignette Performance summarized by a single value providing the relative performance of the assessed scenario. This final value can be used to evaluate the sensitivity of the various space missions' capabilities on the scenario performance. We note that Figure 3.6 provides only a subset of the mission threads captured in the WSDM (as discussed in a later section) and is only intended to illustrate the process steps used in the approach.

Figure 3.5. WSDM Description



[19] WSDM was continually being updated during the course of this research. As of March 2018, WSDM had 15 space missions and 27 joint mission threads.

Figure 3.6. WSDM Approach



Output from Method

The output provided by this approach is a qualitatively based assessment of the effectiveness of a joint warfight for given space performance. This metric provides decisionmakers with a high-level view of the space domain contribution to the warfighter and the effects of degradation of that domain on joint mission capabilities (through sensitivity analyses).

Types of Tools Used

The WSDM methodology is based on a mission dependence matrix to estimate the joint warfighting capability. For example, the matrix captures the dependency of an air domain strike mission on the Global Positioning System (GPS) and ISR and estimates the impact on the mission if GPS and/or ISR capabilities are degraded. We categorize this method as a campaign-level model because it relies on mission performance inputs to determine the performance of a scenario.

Key Inputs and Assumptions

The principal inputs to the calculations are the space mission capabilities and their interdependencies, and the dependence of terrestrial operations on space missions. These inputs are provided by subject-matter experts and are low-fidelity estimates because they do not account for the specific conditions and environment involved in a given scenario. The WSDM currently captures ten space mission areas (and their interdependencies), and 23 joint mission threads along with their reliance on the space mission areas.[20]

Advantages

The output of the model provides decisionmakers with a high-level view of combined missions and assesses the effects of space systems on the joint warfighter capabilities. Speed of analysis is also an advantage.

Limitations

The principal limitations associated with WSDM are twofold: (1) the low fidelity of the approach and (2) its reliance on qualitative subject-matter expert inputs used to assess the overall joint mission performance.

Summary of Five Analytic Methods

We summarize the five analytic methods along with their advantages and limitations in Table 3.1.

As described earlier, it is possible to construct hybrid methods that adopt features from several methods, which could alter the assessment of advantages and limitations. We made no attempt to optimize the methods, and instead we described the methods as they have been used in applications. Our aim was to provide a representative characterization of available analytic methods. We also note that it is possible to alter some of the underlying assumptions. For instance, we note that the tactical drawdown method assumes that Red intends to draw down Blue capability as rapidly as possible. This assumption could be replaced with some other underlying assumption about Red intentions, which could affect advantages and limitations.

As will become apparent in Chapter 4, the existing methods lack adequate uncertainty analyses, which are needed to address an important shortfall.

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[20] The ten space mission areas are: WB, narrowband (NB), protected satellite communication (PSC), PNT, ISR, missile warning (MW), weather, support operations (SptOps), space control (SC) and SSA. The 23 joint mission threads are: deep strike, theater airlift, defensive counter air (DCA), air refueling, offensive counter air (OCA) sweep, close air support (CAS), electronic attack (EA), theater ballistic missile (TBM) hunt, suppression of enemy air defenses (SEAD), joint forcible entry options (JFEO) amphibious assault, tactical ISR, fire support, entry into theater, tactical maneuver, JFEO air assault, integrated air and missile defense (IAMD), surface warfare (SUW), strike warfare (STW), antisubmarine warfare (ASW), mine counter measures (MCM), ISR phases 0 and 1, Blue force tracking, and strategic missile warning.

Table 3.1. Five Existing Analytic Methods

Analytic Method	Modeling Level	Advantages	Limitations
Tactical drawdown	Mission and engagement level	Ease of understanding	Assumes Red intent to rapidly draw down Blue; lack of cross-domain and warfighter effects
Operational drawdown	Mission and engagement level	Ease of understanding; depicts degradation over multiple phases of conflict	Requires large number of assumptions about scenario; lack of cross-domain and warfighter effects
Static force structure comparison	Engagement-level modeling and simulation	Captures implications for Red	Assumes Red intent to rapidly draw down Blue; no depiction of degradation over time
TVT	Campaign level	Captures multiple time lines; speed of analysis; captures interdependencies in space missions	Lower fidelity due to simplicity
WSDM	Campaign level	Assesses effects on joint warfight; speed of analysis	Lower fidelity due to simplicity; reliance on qualitative inputs

Analytic Methods for Assessing Air Base Resilience

An observation about the five analytic methods for SMA assessments is that there is no one preferred method. Each method was useful in providing decision support in its particular use case. There are advantages and disadvantages depending on specific decisionmaker needs. This is the case for analytic methods to similar assessments in other domains. To illustrate this point, we describe analytic methods used in assessments of air base resilience. Air base resilience provides a particularly interesting example of resiliency in warfare because it has much in common with space resilience and, more broadly, SMA.

SMA is defined in *Joint Publication 3-14: Space Operations* as previously stated. While there is no common DoD definition of air base resilience, we use the definition for "operational resilience" offered in Hagen et al. (2016, p. 3) as it applies to air operations at air bases. It is defined as "the capacity of a force to withstand attack, adapt, and generate sufficient combat power to achieve campaign objectives in the face of continued adaptive enemy action."

Both air base defense and SMA have dispersed responsibilities. From a C2 perspective, the JFSCC has primary responsibility for the defense of space, and the Joint Forces Air Component Commander (JFACC) has primary responsibility for air base defense when also serving as the area air defense commander (AADC). In terms of training, organizing, and equipping, responsibilities for the defense of space are interagency (DoD and IC) and, in the case of air base defense, the responsibilities are divided among the services (e.g., Navy Aegis and Army Patriot III).

Another similarity is that active and passive measures proposed for air base defense map easily into the measures of SMA described in *Joint Publication 3-14*. We provide a mapping in Table 3.2.

Table 3.2. Mapping Between Air Base Resilience and SMA Measures

Air Base Resiliency Measures	SMA Measures
Hardening (e.g., aircraft shelters)	Protection (e.g., hardening satellites)
Dispersal (on base)	Disaggregation (e.g., disaggregate tactical and strategic SATCOM)
Dispersal (across many bases)	Distribution (e.g., across allied, commercial, and military platforms)
Distance	Diversification (via alternative orbit, such as Tundra orbit)
Capacity increases	Proliferation
Camouflage, concealment, and deception	Deception
Postattack recovery/repair capability	Reconstitution

Defending air bases or space capabilities from attacks by a near-peer adversary would be challenging missions, and the U.S. military has little to no recent experience with either one.[21]

While there are many similarities, a key difference is that assessments of air base resilience date back many decades (see, for example, U.S. Air Force PROJECT RAND, 1952), whereas space as a warfighting domain is a relatively new concept (there was limited consideration of conventional warfare extending to space during the Cold War because an attack in space would be a likely precursor to a nuclear exchange, as discussed previously).[22]

Recent assessments of air base resilience appear to be providing useful decision support to decisionmakers, as evidenced by the impact the assessments appear to be having on decisions made. For instance, OSD issued a fiscal year (FY) 2015 Resource Management Directive to the USAF to purchase base defense capabilities totaling $280 million, a decision which appears to be supported by recent analyses.[23] We briefly describe two example analyses that supported air base resilience–related decisions in the following sections.

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[21] Still, the United States has vastly more experience with air base attacks than space attacks. World War II opened with devastating attacks on U.S. airfields on Oahu, Hawaii, and in the Philippines. During the Korean War, the United States experienced significant ground attacks and modest air attacks on airfields. During the Vietnam War, U.S. airfields were attacked almost 500 times by ground forces and the USAF lost more aircraft to ground attacks on its airfields than it did in air-to-air combat over North Vietnam. During the Cold War, the USAF expected heavy air and missile attacks on its airfields in Europe and put great effort into defending them. Since 1953, USAF bases in Korea have maintained substantial defenses against air and ground attack and continue to make such defenses a training priority. During Operation Iraqi Freedom, Balad Air Base was attacked more than 1,000 times by rockets.

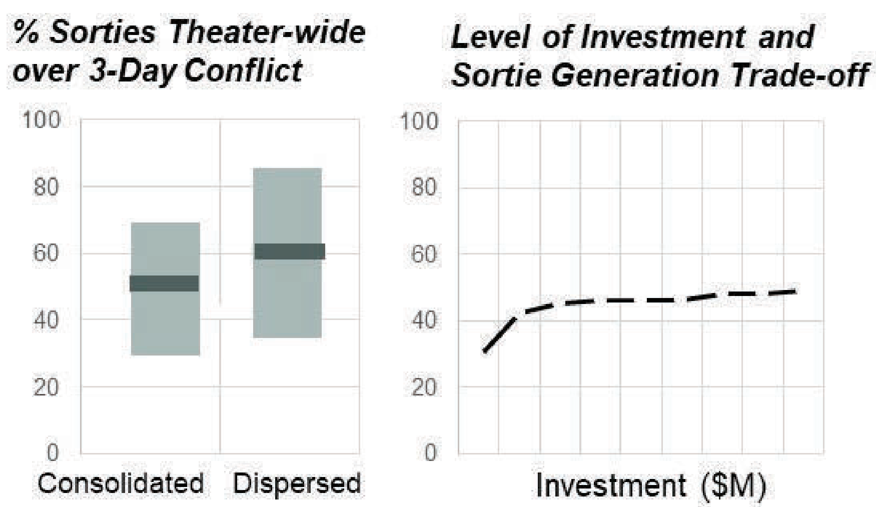
[22] There are additional differences between space systems and aircraft that are worth noting here. Space acquisition program mission assurance can be measured by delivery to orbit and checkout operations; currently, space systems are not built in a production line (because the quantities are small), whereas the vast majority of air vehicles are built in a production line. Almost all space vehicles, once launched, can only be repaired or have their capabilities adjusted electronically, generally through software changes developed on the ground. The general battle rhythm of space operations is much slower than those of air operations. Similarly, the time line for reconstitution of space capabilities in comparison with air capabilities is much slower in most cases. Space debris presents a unique challenge for mission assurance.

[23] In particular, it is supported by the body of work using the combat operations in denied environments (CODE) capability as described in Thomas et al. (2015). See also Lostumbo et al. (2013).

Method 1: CODE Analysis

RAND researchers have conducted a body of analyses using the CODE methodology. Those analyses have been used to inform decisions concerning investment options, force posture, and theater-shaping strategies for air base resilience (Thomas et al., 2015). CODE's overarching analysis approach is to analyze alternative COAs, such as air base defense investment options, basing posture, and attack vectors, through scenarios that assess their effects on Blue's ability to generate sorties when air bases are under attack. Figure 3.7 shows an example output. The analysis used several metrics to provide insights into the trade space in investment options. The primary metric for CODE analyses is sortie generation. For instance, the analysis depicted in Figure 3.7 compared the resilience of two basing alternatives (dispersed and consolidated) by computing the percentage of sorties generated theaterwide under a wide range of attack vectors (the vertical span of results shown on the left plot in Figure 3.7). To inform the trade space between air base resilience measures and cost and to identify the "knee of the curve," the analysis examined the percentage of sortie generation for optimized investment strategies, capped by cost (shown in the right plot in Figure 3.7).

Figure 3.7. Example of CODE Methodology



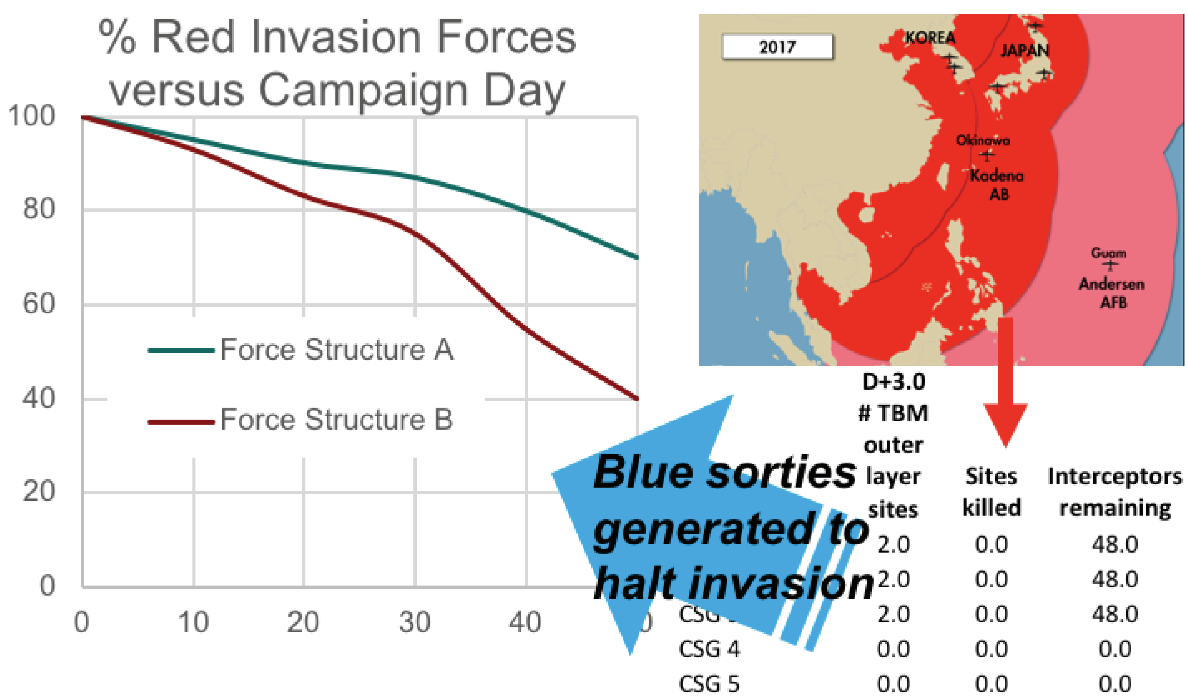
SOURCE: Notional analysis results based on Thomas et al. (2015).

Although this CODE analysis did not assess the impact of air base resilience investments on the effectiveness of various air missions (e.g., DCA and strike) nor on the campaign outcome, these metrics were useful for the decisionmakers in informing their COAs to enhance air base resilience. This usefulness may be partly because the air operations community intuitively understands the combat power associated with sortie generation. The analysis results also included the type of sorties generated (e.g., DCA or strike) and the percentage of aircraft lost, as those metrics provide additional insights into the value and risks of various air base resilience measures.

Method 2: Campaign Outcome–Guided Mission-Level Analysis

We describe another example of an air base resilience analysis that supported USAF fighter and bomber force structure decisions (Heginbotham et al., 2015). This analysis employed multiple analytic methods and tools, including a synthetic theater operations research model (STORM) campaign and a separate spreadsheet model for conducting air base attack analysis. STORM results were used to estimate the amount of damage that needed to be imposed on an invading ground force over a period to halt an invasion. Spreadsheet models were then used to estimate the amount of ordinance that needed to be delivered by aircraft operating from bases in the region to impose this damage. Finally, another set of models was used to estimate the number of Blue strikes on ground forces that could be generated from those bases subject to Red attacks on those bases. The output is depicted in Figure 3.8.

Figure 3.8. Example of Campaign Outcome–Guided Mission-Level Analysis Method



SOURCE: Notional analysis results based on Heginbotham et al. (2015).

It is worth noting that both methods for assessing air base resilience employ metrics that are likely to be familiar to decisionmakers from a variety of backgrounds. The first method uses the number of sorties that can be generated in a theater over a three-day period. While that does not directly measure performance against a campaign objective, it can be related to operational outcomes that affect campaign objectives. The second method uses the percentage of invasion forces halted versus the number present on campaign day.

Summary

Many different analytic methods have been developed and used to provide SMA assessments. We describe five analytic methods, and there are advantages and disadvantages to each depending on the decisions under consideration. There does not appear to be one superior metric and associated analytic method. This is also the case for similar analyses in other domains, and we described two analytic methods for assessing air base resilience to illustrate this point.

While this chapter described likely advantages and disadvantages of alternative analytic methods, in the next chapter we discuss shortfalls in recent SMA assessments as described to RAND researchers by analysts and decisionmakers.

4. Shortfalls

This chapter describes shortfalls in recent assessments of SMA for meeting decisionmaker needs. Those assessments were presumably made using available analytic methods, such as the five that are described in Chapter 3. This chapter is primarily based on feedback gathered during semistructured interviews with decisionmakers, though we also include shortfalls reported by analysts.

Before proceeding, it is important to note that analytic methods for assessing SMA and shortfalls are moving targets. The research team observed evidence of progress in closing many of the shortfalls that are associated with past SMA assessments. Also, shortfalls in SMA assessments can result from a variety of factors besides analysis. For instance, an assessment has to be effectively communicated to the right person (decisionmaker) at the right time (prior to a decision milestone) to be useful. Finally, we note that the shortfalls in SMA assessments are not unique. Similar shortfalls exist for assessments in other domains. However, the shortfalls may be more severe for SMA assessments for a variety of reasons that we will discuss in this chapter. Hence, it is an objective of this report to recommend actions that can help accelerate closure of the shortfalls and aid efforts already under way.

Shortfall 1: Lack of Established Baseline and Uncertainty Bounds for Inputs and Assumptions Needed for SMA Assessments

A common theme in our interviews with analysts is that there is a lack of established baseline and uncertainty bounds for inputs and assumptions that are needed for many assessments of SMA. Analysts at two organizations within the NSS community indicated that a standardized baseline scenario is needed to link SMA assessments to operations in the terrestrial domains.[24] The scenario would need to provide detailed information about space capabilities and objectives for operations in the space domain, and the information would be used as inputs to SMA assessments.

Analysts at another organization indicated a general lack of available threat models and also indicated that when threat models are available, they are often not standard.[25] Standardized threat models require the application of engineering judgment to fill gaps in available intelligence about long-range threat capabilities. Notional examples might include the delta-v budget for a future missile threat, or the projected field-of-view of a seeker for an advanced adversary

[24] Interviews with staff at the National Reconnaissance Office, Office of Enterprise Assessments, January 31, 2018; and interviews with staff at the SSDP, February 6, 2018.

[25] Interviews with staff at AFSPC, 2018.

weapon that is still under development. While the engineering judgment could be subject to uncertainties, having a standard set of assumptions used for SMA assessments across the NSS analytic community would at least facilitate comparison or integration of assessment results from different efforts and provide a common baseline from which sensitivity analyses could be conducted. It appears that the Space Threat Assessment Cell (STAC) may be a suitable organization for developing threat models for long-range threat capabilities. The STAC has both Title 10 and Title 50 responsibilities, which enable it to integrate information spanning multiple parts of the NSS community. The STAC does not have intelligence production responsibilities and has a longer-term focus than intelligence production organizations. This gives it the latitude needed to apply engineering judgment. But the STAC is a relatively new organization, has few analysts, and may take time to develop the required expertise.[26]

Some analysts within the NSS community indicated that they lacked input information about Blue capabilities that are needed for SMA assessments.[27] This includes a lack of information about Blue space and counterspace capabilities and, in some cases, a lack of information about Blue capabilities in other domains (e.g., air).

The fact that space as a warfighting domain is a relatively new concept is likely a contributing factor to the shortfall in available input data and assumptions. Many of the threats and countermeasures are still evolving, so many of details about them may be unknowable or highly uncertain. Space and counterspace capabilities tend to be highly sensitive and protected information for the United States and for potential adversaries. This creates challenges for intelligence collection. Also, the classification level and need-to-know access of Blue space and counterspace capabilities place strict limits on the ability to provide information for SMA assessments. The challenge this creates is not unique to the NSS, as other communities (e.g., combat air or subsurface warfare) also need to protect sensitive information in similar ways. However, according to a special security officer we interviewed, the fragmentation of the NSS community exacerbates the challenges. It is not uncommon for an SMA assessment to rely on a mix of information protected by multiple levels of classification, multiple special access channels, subcompartments, and reserve words spanning both DoD and the IC. This fragmentation can create significant challenges for personnel, facilities, and information technology associated with SMA assessments.

The lack of established baseline and uncertainty bounds for inputs and assumptions needed for SMA assessments may seem like a challenge for analysts as opposed to a shortfall in meeting the needs of decisionmakers. However, decisionmakers highlighted the lack of transparency and too much subjectivity as areas of concern in past SMA assessments, which are related to this shortfall. They felt that the assumptions were not validated or sufficiently vetted. For instance, one decisionmaker pointed to an analysis that assumed perfect C2 and SSA on the Blue side as

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[26] Interviews with staff at the Office of the Director of National Intelligence STAC, January 30, 2018.

[27] Interviews with staff at the SSDP, February 6, 2018.

being unrealistic. Additional analyses are desired by decisionmakers to validate assumptions. Similarly, with disparate organizations working on different models, some decisionmakers suggested that the models need to be validated or vetted because the recommended COA could be biased. The FY 2018 program decision memorandum (PDM)-directed survey on analytical support nodes for NSS also found disparate analytic baselines (e.g., data and assumptions) as a key issue. Aside from the concern about the potential for biases, decisionmakers desire common understanding of assumptions and vetting of assumptions and models to enable a discussion among different organizations (e.g., DoD and the IC). As discussed earlier, a diverse set of stakeholders is involved in many investment, force structure, and requirements decision processes.

The desire for transparency, validation, or independence in decision support analysis is not unique to space. The Navy relies on OPNAV N81 for Navy-wide independent assessments to inform PPB decisions (Blickstein et al., 2016). The U.S. Army's Training and Doctrine Command provides analytic baselines that the analytic community can use for a range of decision support analyses. Similar organizational and process improvements are being considered for the NSS (AFSPC, 2018).

Research completed in 2016 suggests that perhaps multiple baselines are needed rather than one to ensure adequate excursions for uncertainty analysis. Davis says

> [t]here is a clear need for common data sets to allow the comparison of analyses using the same assumptions (a long-standing demand by senior leaders who receive multiple briefings that cannot be compared directly). The tendency, however, is to never get around to the uncertainty analysis. The solution is not to avoid baselines but to demand the excursions (Davis, 2016, p. 56).

Shortfall 2: Lack of Available Methods for Assessing Social-Behavioral Aspects of SMA Assessments

Decisionmakers and analysts described shortfalls related to the social-behavioral aspects of SMA assessments. For instance, operators at the NSDC expressed the need for SMA assessments to help them anticipate adversary responses to space operations.[28] As another example, members of a recent space AoA team we interviewed indicated a need for assessing potential adversary targeting priorities and preferences for counterspace operations. Additionally, the AoA team needed a method for assessing restorability time lines for space alternatives.[29] Those time lines depend in part on human decisionmaking for C2, and quantitatively assessing the contributions of human decisionmaking in C2 organizations to operational outcomes remains elusive (Alkire, 2018, p. xii). Another important example is a shortfall in assessing the role of space deterrence in

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[28] Interviews with staff at the NSDC, February 7, 2018.

[29] Interviews with the WCS AoA team, December 5, 2017.

SMA assessments.[30] Understanding and predicting adversary and grey actors' intents can be important for the defense of space. Knowledge and information on the intent and capabilities of these actors can help Blue anticipate Red offensive actions and responses to Blue space operations. All of these examples involve social-behavioral assessments of human decisionmaking.

A shortfall in methods for assessing the role of space deterrence in SMA is not surprising given that concepts for space deterrence are still evolving. During the Cold War and until recently, space deterrence has been intertwined with nuclear deterrence as an integral part of the nuclear umbrella designed to deter Russia and China from a first nuclear strike (Pawlikowski, Loverro, and Cristler, 2012). As the world order has evolved and geopolitical conditions have changed, there has been a shift in the use of space as a supporting function to conventional conflicts as opposed to space as part of the U.S. strategic agenda. This shift is due in part to the fact that the United States has enjoyed significant superiority in space capability, and because the United States has not been challenged in space. Today, space deterrence is emerging as a separate concept in its own right. Some working definitions that have already emerged offer some insights into the differences between space and nuclear deterrence. For instance, Krepon (2013, p. 15) defines *space deterrence* as "deterring harmful actions by whatever means against national assets in space and assets that support space operations. Analogously, nuclear deterrence is defined as deterring harmful actions by means of nuclear weapons."

The topic of space deterrence continues to be an area of active research. For instance, Jafri and Stevenson define two types of space deterrence:

- Type 1 Space Deterrence: This type of space deterrence has as its strategic goal space asset infrastructure security. This includes the prevention of spillover of conflicts in other domains into space (multi-domain war) that target space capabilities.
- Type 2 Space Deterrence: The second type of deterrence is the prevention of the weaponization and the basing of multi-domain weapons in space (Jafri and Stevenson, 2018, p. 6).

Deterring harmful actions against space capabilities helps to provide for SMA. Similarly, providing for SMA may enhance deterrence if a potential adversary believes it cannot meet its objectives (that is, deterrence by denial). But it may also incentivize adversaries to develop new and improved capabilities to threaten space assets in the future. Clearly, space deterrence and SMA are related, yet space deterrence is not an element of SMA as defined in joint doctrine. We will return to the subject of space deterrence in the next chapter, which describes ways to address the shortfalls.

[30] Interviews with staff at the OUSD(AT&L), 2017; and interviews with staff at OSD CAPE, 2017.

Each example just described requires a social-behavioral assessment: adversary responses, adversary target preferences, human decisionmaking for C2, and deterring actors from taking harmful actions.

Shortfall 3: Lack of SMA Assessments Linking Space to Terrestrial Warfighting Operations

Another shortfall is a lack of SMA assessments that measure the value of SMA in the context of a joint warfight. Some interviewees expressed that a metric beyond an individual system–level metric is needed. Others also pointed to the fact that past analyses have focused on the space portion in measuring resilience and the "so-what" factor was missing. That is, the value of SMA through the lens of protecting satellites is different than looking at it through the lens of warfighting effects that space provides to operations in other domains.

More recently, thinking of SMA in the context of joint warfighting is gaining more traction. The FY 2018 PDM-directed survey on analytical support nodes for NSS advocated that quantifying and communicating warfighter dependence on space would enable investment prioritization across domains (Bialek, 2017). The Space Analysis Vector Summit also highlighted senior leaderships' demand for better understanding of the impact of space on joint warfighting (AFSPC, 2018).

In many cases, the impact of degraded or lost space capabilities on the joint warfight and the associated operations in other domains are "knowable" and can be assessed quantitatively. One example would be quantifying the impact of degraded PNT on the accuracy of weapon strikes and linking such an impact to trade-offs in munitions and weapon delivery assets. Similarly, the impact of degraded space-based ISR on the targeting and battle damage assessment can be assessed and related to mission- and campaign-level outcomes. However, there are also examples in which quantifying the impact of a degraded space capability on operational outcomes can be challenging. For instance, consider the impact of degrading SATCOM services provided to a C2 element in the context of a joint warfight. It may be possible to quantify the impact of counterspace weapons on the SATCOM architecture and to deduce the implications for the ability of the C2 element to communicate (e.g., it may be possible to assess communication data rate and latency implications). But quantifying the effect of that degraded communication on operational outcomes would require quantifying the impact on human decisionmaking by the C2 element. Hence, the challenge for this assessment is not directly associated with space at all. It stems from the fact that quantitatively assessing the contributions of human decisionmaking in C2 organizations to operational outcomes remains elusive, as previously mentioned (Alkire, 2018, p. xii). That challenge is not unique to SMA assessments and affects similar assessments in other domains.

In our interviews, decisionmakers articulated that the impact on the joint warfight needed to be communicated in tangible terms that senior leadership can process and that adequately convey the risk. The decisionmaker community is very diverse, including members with little space expertise. There is a desire to use more-concrete terms that convey operational risks and to use warfighting terminology when communicating the value of SMA. One interviewee said, "Probability of kill values don't work for senior leaders."

Linking space to the terrestrial fight may require bringing together highly sensitive and compartmented information on capabilities in multiple domains and from many organizations, and limitations on this information-sharing can contribute to the shortfall. Also, the fragmentation of the NSS community may create challenges for bringing together information about space capabilities and thereby contribute to this shortfall.

Shortfall 4: Lack of SMA Assessments Spanning Multiple Mission Areas

Decisionmakers expressed challenges in making trade-offs between SMA options for one space mission area over another. An example of these challenges is found in assessing whether SMA enhancements for protected communications are more important than those for GPS. This shortfall is similar to the shortfall in assessments linking space to operations in other domains. The fragmentation of the NSS community leads to fragmentation in responsibilities for different space mission areas and is likely a contributing factor to this shortfall.

Summary

This chapter identified four shortfalls related to a lack of input information and standardized assumptions, lack of methods for assessing social-behavioral aspects, lack of assessments linking space to operations in other domains, and lack of assessments spanning multiple space mission areas. We also described several contributing factors. In the next chapter, we describe ways to address these shortfalls.

5. Ways to Address the Shortfalls

As described in Chapter 4, the shortfalls are not unique to SMA assessments but are more severe than they are for similar assessments in other domains. Contributing factors to the severity include the relative newness of space as a warfighting domain, fragmentation of roles and responsibilities within the NSS community, and challenges associated with compartmentalization of data and information associated with SMA assessments. There are shortfalls (labeled S1 through S4) in

- (S1) established baseline and uncertainty bounds for inputs and assumptions needed for SMA assessments[31]
- (S2) available methods for assessing social-behavioral aspects of SMA
- (S3) SMA assessments linking space to terrestrial warfighting operations
- (S4) SMA assessments spanning multiple mission areas.[32]

In the remainder of this chapter, we describe ways to address the shortfalls.

Joint Space Warfighting Forum

The JSWF was funded with $25 million over five years and is set to end in FY 2020. It brings together analysts from across the NSS community for monthly, classified video teleconferences. These meetings are used to discuss challenges, share ideas for addressing those challenges, and share best practices, including for SMA assessments. This effort directly helps to mitigate challenges stemming from fragmentation of the NSS community. The JSWF was cited by numerous organizations as helping to accelerate the closure of shortfalls and to address challenges. There are ongoing discussions about the future of the JSWF beyond FY 2020 and, if it has a future, how it should be organized and funded. Those details are beyond the scope of this report. However, we recommend that leadership in the NSS community continue to fund and support the efforts begun with the JSWF because they may help to address all of the shortfalls identified in this report.

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[31] For example, baseline and uncertainty bounds on PK for an adversary counterspace capability that could be needed for an SMA assessment.

[32] The numbering of shortfalls does not reflect a prioritization.

Enhance Interagency Information-Sharing[33]

Information associated with SMA assessments tends to be highly classified and need-to-know access tends to be very limited. These factors can create a host of challenges, including challenges for finding or developing appropriately cleared and accessed personnel, approving facilities for storing data and for analysis, approving computing systems and associated networks, approving software, and challenges in the need to comingle from different clearance levels and access channels for analysis and results. The challenges for analyses stemming from the high levels of classification and compartmented access are not unique to the space community. However, these challenges are likely more severe for SSA assessments because of the highly sensitive nature of those assessments and because of fragmentation of the NSS community. It is not uncommon for an SMA assessment to rely upon a mix of information protected by multiple levels of classification, special access channels, subcompartmented information, and reserve words spanning DoD and the IC.

Senior leaders in the NSS community should undertake an initiative to identify key information-sharing needs to support SMA assessments. In some cases, the information owners may be able to establish security constructs with terms of reference to facilitate information-sharing while protecting sensitive capabilities without having to open up a sensitive capability or activity to a larger number of people. Some historical examples are described in Appendix D. A recent example of a security construct in another domain is the Air Dominance Initiative, which facilitated collaboration and information-sharing among the Defense Advanced Research Projects Agency (DARPA), USAF, and Navy (McLeary, 2015; Defense Science Board, 2016). Information owners should review and revise security classification guides as needed and provide appropriate representation of capabilities at multiple security levels and access channels to facilitate information-sharing. This recommendation can help address all of the shortfalls.

Incentivize Innovation and Acceleration in Progress

We looked for examples in which actions by senior leaders have resulted in significant progress in analytical methods. One example that appears relevant is found in wargaming methodologies, which appear to have gone through a renaissance since Secretary of Defense Chuck Hagel established a "Defense Innovation Initiative" in 2014 (Hagel, 2014). In early 2015, Deputy Secretary of Defense Robert Work issued a memorandum constituting a new wargaming program and directing that insights from the program influence the planning, programming, budgeting, and execution process (Work, 2015). Later in 2015, Navy Secretary Ray Mabus issued a memorandum directing reinvigoration of Department of the Navy wargaming and the

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[33] According to feedback from the Office of the Assistant Secretary of the Air Force for Space Acquisition and Integration in 2020, the Space Analysis Consortium is undertaking an effort to enhance interagency information-sharing.

integration of wargaming into program development (Mabus, 2015). In 2016, Secretary of Defense Ash Carter cited investments totaling $55 million to "reinvigorate and expand wargaming efforts across the Defense Department" in testimony to the Senate Armed Services Committee for the FY 2017 Budget Request (Carter, 2016, p. 16).

Senior leaders in the NSS community may be able to take similar actions to drive innovation and progress in analytical methods for SMA assessments. We recommend that senior leaders in the NSS community articulate that innovation and progress in methods for SMA assessments are a high priority, and that those leaders work to establish and fund an SMA Innovation Initiative to accelerate the closing of the shortfalls.

Sensitivity Analyses

Sensitivity analysis refers to any method that assesses how a system or model's output varies (and how strongly) because of perturbations in any of the variables that determine the output. These variables may be design variables—inputs to system performance chosen as part of the design process—or external variables representing threats and external perturbations to the system. They may also be metrics that drive decisionmaking processes, such as performance score weights.

At a minimum, SMA assessments should employ sensitivity analyses to help cope with the lack of established baseline and uncertainty bounds for inputs and assumptions. Appendix B provides a summary of sensitivity analysis techniques with specific application to SMA assessments.

However, sensitivity analyses are designed to evaluate excursions of a few variables in the vicinity of a starting point. For more complex SMA assessments with uncertain inputs, more-sophisticated methods are needed, such as recent methods designed to support decisionmaking under uncertainty, which leads us to the next recommendation.

Decisionmaking Under Uncertainty and RDM Methods[34]

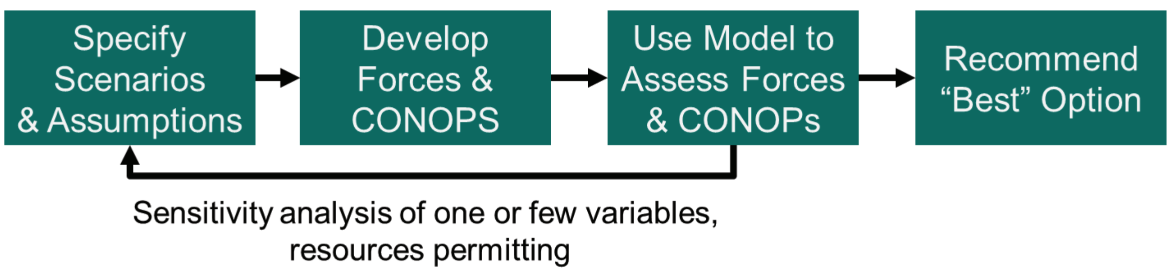
As discussed, SMA assessments are not the only assessments that rely on highly uncertain inputs and assumptions. Methodologies have been developed to explicitly deal with these types of uncertainties, including RDM (Lempert and Collins, 2007), robust optimization (Ben-Tal, El Ghaoui, and Nemirovski, 2009), assumptions-based planning (Dewar et al., 1993), capability-based planning (Johnson, Libicki, and Treverton, 2003; Davis, 2002), and portfolio analysis (Davis, Shaver, and Beck, 2008; Davis, 2014). Analytic methods to support decisionmaking

[34] According to feedback from the Office of the Assistant Secretary of the Air Force for Space Acquisition and Integration in 2020, an RDM capability was in the process of being used operationally for the first time. It is built on the Genetic Resources for Innovation and Problem Solving (GRIPS) architecture developed by Aerospace Corporation.

under uncertainty are an active area of research, and a comprehensive treatment is beyond the scope of this report. The reader who is interested in delving more deeply into the subject is encouraged to refer to the publications from the Society for Decision Making Under Deep Uncertainty (undated). For the purposes of this report, we describe the application of RDM methods.

The early application of RDM methods was for assessments of climate change. These solution approaches can help to address the functional need for uncertainty analyses to address the shortfall in established baseline and uncertainty bounds for inputs and assumptions needed for SMA assessments (S1). To illustrate how, we first describe scenario-based planning methodologies, which are pervasive in DoD, including for SMA assessments. We then describe RDM methodologies and how they help to cope with uncertain inputs and assumptions that would typically be required for scenario-based planning (Figure 5.1).

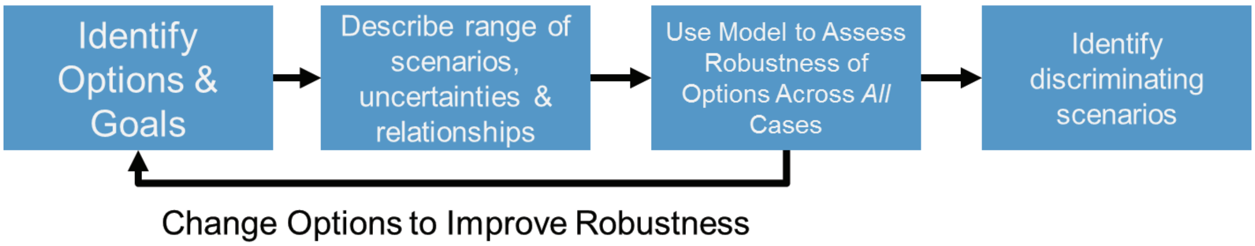
Figure 5.1. Scenario-Based Planning Methodology



The scenario-based planning methodology involves a sequence of three basic steps. In response to an identified planning challenge, the first step is to identify and articulate an applicable set of scenarios. The scenarios are generally representative of the Presidential Contingency Planning Guidance and the missions assigned to the military through the U.S. defense strategy, and they are posited sometime in the future—generally five years out—to align derived assessments with PPB processes. A range of uncertainties regarding the scenario are resolved by making assumptions about specific adversaries; U.S. and adversary wartime objectives; warning times, including a road-to-war; rules of engagement; and access to bases in and overflight of partner territory. The second step involves elaborating the scenarios from the first step with baseline forces and CONOPS for Red and Blue to employ in the scenarios. The last step is assessment. Assessments include sufficiency analyses (i.e., quantitative comparisons of the supply of and demands for forces) and proficiency analyses (i.e., modeling and analysis at the engagement, mission, and campaign levels). These assessments are generally conducted by using the scenarios, forces, and CONOPS developed in the prior steps. Often, additional assumptions are introduced to reconcile uncertainties about the performance of specific weapon systems, environmental conditions, tactics, human factors, and others. On the basis of these assessments, conclusions are drawn to form a baseline assessment of the programmed force and to recommend potential enhancements.

Next, we describe the alternative RDM methodology (Figure 5.2).

Figure 5.2. RDM Methodology



The first step of the RDM methodology is to start at what was the end of the process of scenario-based planning: the decision. That is, instead of starting by identifying a set of scenarios, we instead ask questions about end objectives and the options available to meet those objectives. In the context of force planning, the options may pertain to alternative force structures, capabilities, or CONOPs. Second, RDM requires identifying the factors that may influence the decision. The factors group into one of four categories:

- key variables and potential configurations of those variables (which the analyst may control but cannot foresee ahead of time), reflecting uncertainty
- exogenous key variables, which represent future actions of external actors or states of the world over which the analyst has no control
- suppositions regarding the causal mechanisms between key variables and decisions, leading to outcomes
- different metrics used to characterize those outcomes as good or bad.

Third, RDM calls for a strategy of performing a large number of compound computational experiments to test the implications of alternative assumptions regarding uncertainties. This strategy involves applying options identified in the first step against the many cases generated by the combinations of different assumptions and then assessing outcomes across the full range of measures identified in the second step. This competition among different options against a level playing field of many cases is an iterative process with learning and refinement of both the set of alternative futures and the composition of the options. The computational experiments rely on a simple, transparent, and fast-running model to facilitate rapid and wide-scale exploration of the scenario space. The availability of such a model, or feasibility of developing one, naturally depends on the decision.

The resulting database derived from the trials of the alternatives may then be explored for those cases in which each option failed to meet the minimum standards set for one or more outcome metrics. We may then use data-mining techniques to understand what is systematic across the failure modes for each option and identify the factors that discriminate the options.

There may be many cases in which all options succeed or fail to meet the minimum goals; RDM refers to these scenarios as unhelpful for discriminating the options under consideration. But there will likely be other cases in which the options diverge in the success or failure of goals, revealing themselves as discriminating factors that should attract decisionmaker attention. Decisionmakers may then ask whether these discriminating cases are situations in which they should accept or mitigate risk. The ability to focus attention on the uncertainties that should affect the decision—the uncertainties that matter, so to speak—is a virtue of RDM.

Whereas the scenario-based planning methodology began with a selection of uncertain inputs, such as details regarding a scenario, the RDM methodology instead uses a process to discover and develop increasingly robust force plans and to derive scenarios that may stress the candidate force plans, given the input policy goals.

Appendix A provides more information about RDM methodologies. It also applies an RDM methodology to a notional SMA assessment for on-orbit refueling (OORF). Many approaches to SMA can be enabled by OORF, such as

- reactivating retired satellites (reconstitution approach)
- increasing the number of satellites via a service life extension program (proliferation approach)
- enhancing maneuver capability by refueling (protection approach)
- enabling rephasing or repositioning of a constellation in wartime (deception approach).

The notional OORF assessment illustrates how factors that would typically be uncertain inputs with traditional assessment methods, such as scenario-based planning, actually become outputs. For instance, the OORF assessment illustrates how the RDM methodology outputs a range of values for the PK associated with a counterspace weapon that drives the policy goals that are inputs to the methodology. With scenario-based planning, by contrast, the PK associated with a counterspace weapon would likely be an input and subject to uncertainty.

We recommend that analysts within the NSS community employ RDM methodologies to help identify robust solutions in the face of highly uncertain inputs and assumptions. Appendix C provides a detailed example that illustrates how an RDM methodology can help address shortfall S1.

Assessing Implications of Space Deterrence for SMA Assessments

Incorporating the implications of space deterrence into SMA assessments can be desirable because deterring an actor from causing harm to a space system enhances SMA. When deterrence implications are incorporated, we recommend that the distinction is carefully communicated to avoid confusion because space deterrence and SMA are not the same thing. It may also be important to distinguish space deterrence from other forms of deterrence, such as nuclear deterrence.

Detailed assessments of space deterrence typically require methodologies from the social sciences because deterrence involves influencing human decisions. However, an effective approach for incorporating implications of space deterrence into SMA assessments is to evaluate corner cases, which we describe by example. Consider an SMA assessment of a space mission architecture in the context of a large-scale conflict with a near-peer adversary involving operations across multiple domains. The adversary may or may not be deterred from employing counterspace capabilities against space capabilities associated with nuclear C2 (whether part of the architecture under consideration or not). The corner cases would be to evaluate SMA under two binary conditions: The adversary is deterred from attacking space capabilities associated with nuclear C2, or they would not be deterred. The results of the evaluations from these two binary conditions can bookend the implications of deterrence for SMA while avoiding the need to estimate whether or not an adversary actually will be deterred.

When corner cases are insufficient, emerging analytic models may help to quantitatively assess certain implications of space deterrence. We describe two models here. The first is called Gaming Investment in Space Technology (GIST) (Triezenberg, 2017).

GIST is a two-player game theory model that looks at the development of different offensive and defensive options over time, as well as the evolution of the different space mission architectures and how they affect the overall outcomes. It is an extension of the traditional rational actor game theory model in that it uses prospect theory (Kahneman and Tversky, 1979). This is a theory in behavioral economics that argues that people's risk-taking behavior is much more complex than what traditional theory assumes. By allowing for a more-nuanced behavior for the two game theory actors, GIST creates a more-realistic representation of the behaviors we would actually observe in making decisions about space.

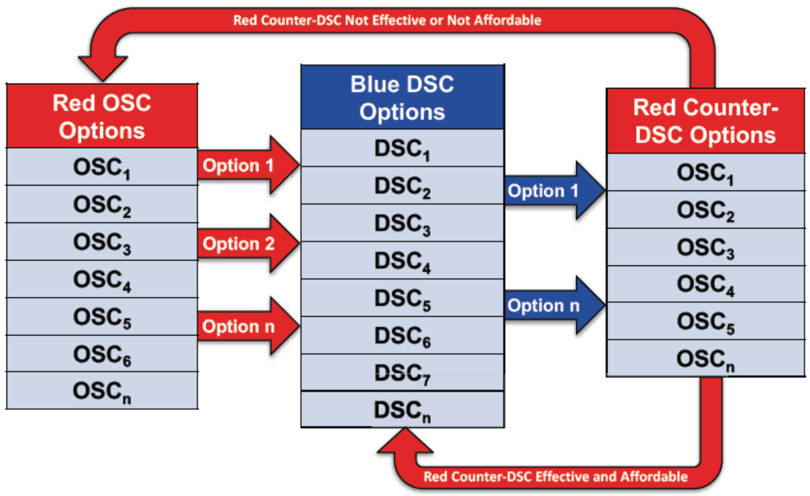
A typical time frame of the game modeled by GIST is ten years. In the beginning of the game, the entities start by projecting ten years into the future. The game proceeds one day at a time (if days exist when nothing is going to happen, those are skipped). During peacetime, the players are trying to maximize their capacity to project military power from space, maximize their political standing in the world, and maximize counterspace capabilities relative to the opponent. During wartime, two more objectives are added: Each side seeks to maximize periods during which it is able to project power from space, while minimizing the opponent's periods. The two players have information about the status of space assets of both sides, weapons and offensive capabilities of both sides, and defensive capabilities of both sides. The actions players can take are to attack, defend, invest in space assets, invest in counterspace weapons, invest in intelligence, or signal their intentions to the adversary. The model can also include uncertainty with, for example, imperfect knowledge, unsuccessful investments, uncertainty of the effects of actions on future power projection, and others. Dependence on space can also change over time. The model does not represent deterrence explicitly, but it models it implicitly in that when both sides have nothing to gain from taking action, and the game has reached a stalemate, deterrence is effectively achieved. It is important to note that the way the model is set up allows the value of political goodwill in the international community to act as a deterrent. For example, if the adversary targets an asset that internationally is not considered a legitimate target (e.g., a National Air and Space Administration [NASA] asset), it may increase its military utility, but it will lose political "capital" (goodwill). If the loss of political standing is big enough, it will deter the adversary from attacking a space asset even if it is militarily advantageous to do so.

GIST is written in Java but provides outputs in spreadsheet format. A key limitation of GIST is that it is very computationally expensive. Also, it is not suitable for a detailed technical architectural trade or for use as a real-time decision or training tool. The model can answer broad space architecture questions, such as

- Should assets be used for both strategic and tactical uses, or should we separate out two distinct space architectures?
- Should we invest in more SSA or more counterspace capabilities?
- Should we invest in more-resilient communications or a more-resilient GPS architecture?

The second model is called the Defense Space Analysis Tool (DSPAT) (Lynch et al., 2018). This model is also a two-player (Red and Blue) game theory model that looks at the development of different offensive and defensive options and how they fare against each other. It is based on combinatorial game theory that uses well-defined rules to establish all possible moves and related payoffs. In its full implementation, it is a three-step game, as shown in Figure 5.4. In the case shown, we start in step one with a set of Offensive Space Control (OSC) options for the Red player (one could start with a blue defensive player instead). The analyst knows the Defensive Space Control (DSC) Blue has available. Based on this information, the analyst decides the most-effective OSC options and employs them. In step two, the analyst examines what Blue has available to counter the Red OSC and chooses the most effective options. Then we look again at the options Red has to counter the Blue DSC options employed. We keep going down the potential combinations of offense, defense, and counteroffense. While this is happening, the tool calculates mission effectiveness, feasibility, escalation risk, and political cost of each combination of options used. By going down the list and scoring the options against these four metrics, we are looking for combinations in which Red is a clear winner, Blue is a clear winner, or neither side reaches a successful outcome with respect to mission effectiveness, political costs, feasibility, and escalation risk. The tool provides the information that guides the analyst to make decisions as to what is acceptable and what is not, either by interpreting the scoring or by assigning different weights in the inputs to the tool in the four areas. As such, and in contrast with the prospect theory model, modeling rational actors or including behavioral aspects of prospect theory can be done by the analyst, but such features are not embedded in the tool itself.

Figure 5.3. Defense Space Analysis Tool



SOURCE: Lynch et al., 2018.

The model is implemented as a spreadsheet, with several scripts. A key limitation is that it does not employ a concept of time, and it does not try to capture the effects of developing and acquiring capability over time. Also, it is not intended to be used for broad architecture trades, such as estimating the need for more communications capability or more SSA. And it would not be applicable to any detailed technical trades for space architectures. The tool can help identify the best defensive space options Blue can employ to specific Red threats, which can provide a useful decision aid for acquisition of Blue DCO capabilities. It is a means to assess ". . . the potential deterrent value and escalation risks of alternative space control options" (Lynch et al., 2018, p. ix). It also provides a methodology for assessing escalation risks and political costs, as well as the effects of observability and attributability (i.e., the effects of the type of attack on political cost for both Red and Blue).

Comparison of the two models is presented in Table 5.1. Although they do have many similarities, they are designed for different types of uses. The prospect theory model is designed for longer-term analyses and architecture trades, while the DSPAT is geared more toward real-time decision support and specifically for employing defensive and offensive space capabilities.

Table 5.1. Comparison of the GIST Model with the DSPAT

Attribute	GIST	DSPAT
Type of model	• Automated two-player game theory	• Analyst-driven two-player combinatorial game theory
Time	• Explicitly modeled daily over a ten-year period	• Not explicitly modeled
Inputs	• Space assets of both players • Weapons of both players • Offensive capabilities of both players • Defensive capabilities of assets	• Offensive capabilities • Defensive capabilities • For each capability, several different attributes, such as its mission effectiveness, feasibility, whether its use is observable and attributable, and non-combatant casualties and collateral damage
Possible actions	• Attack • Defend • Invest in space assets • Invest in weapons that can attack space assets • Invest in intelligence • Signal their intentions to the adversary	• Attack • Defend • Counterattack
Outputs	• Political • Military • Social, Information, and Infrastructure • Total time that either player is "escalated" • Total time that players engage in simultaneous weapons build (i.e., arms race) • Conflict intensity	• Escalation risk • Political cost
Uncertainties modeled	• Move effectiveness • Future power projections • Investment success • Future payoff	• Uncertainty not explicitly modeled
Run time	• High	• Low
Uses	• Broad architecture trades • What information to share with adversary • What information you need about adversary • Strategic decisionmaking • Training space strategic decisionmakers	• Value of different OSC and DSC options • Training space warfighters

SOURCE: RAND research based on Triezenberg (2018) and Lynch et al. (2018).

We recommend that corner cases for space deterrence be evaluated in SMA assessments. When corner case assessments are insufficient, then emerging models such as GIST and the DSPAT might prove useful. This recommendation can help to address the shortfall in available methods for assessing social-behavioral aspects of SMA (S2).

Wargaming

Wargames are most effective when used to investigate human aspects of military operations (Bartels, 2016, p. 3).[35] Focusing the design of a wargame on the investigation of human decisionmaking is what allows the exploration of creative and previously unknown courses of action in the development phase of a plan. Similarly, focusing on human inputs or reactions is also the most effective use of a wargame when analyzing the architecture of a space-based system. Many different facets of military operations can be investigated using wargaming, including the investigation of new concepts, tactics, or uses of equipment. However, wargaming is often most useful for investigating questions about human interaction.

Wargaming is not the panacea of military analysis, however. Trying to predict exactly what the enemy will do based on a wargame is folly and a significant weakness of wargaming when coupled with the power of persuasion that is often associated with high-profile wargames. Often, the lessons participants learn from a wargame are so profound that the participants walk away from the event believing they have the answer to whatever challenge they were presented with. However, even the same individual given the same information is unlikely to make the same decisions every time. The reactions of the opposing side cannot be predicted with 100 percent accuracy through wargaming.

Conversely, the results of wargames should not be completely discounted, despite the fact that those results may not be perfectly accurate. The results of a wargame may lack accuracy in prediction but can provide valuable insight. Often, the insights obtained from wargaming can be complemented by analytic efforts from other forms of analysis, such as modeling and simulation. Using the strengths of wargaming insights into human decisionmaking and combining those results with quantitative analysis can provide the strongest understanding possible for informing decisions (Davis, 2016, Ch. 5).

Wargaming can be used to provide insights into adversary target priorities and preferences as well as adversary reactions to space operations. The WCS AoA team employed a novel wargaming approach to assessing the requirements for restorability time lines associated with alternatives under consideration. Wargaming can also be used to gain insights about space deterrence. We recommend using wargaming methods and combining the results with results from quantitative analyses for SMA assessments. This practice can help to address a shortfall in methods for assessing social-behavioral aspects of SMA assessments.

Campaign Outcome–Guided Mission-Level Analysis

In this subsection, we describe an analytic method that can help link SMA assessments to operations in other domains and enable assessments of SMA spanning multiple space mission

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[35] Wargaming is enhanced when informed by insightful qualitative and quantitative modeling. The importance of qualitative work is described in Davis, 2017.

areas. We call the approach *campaign outcome–guided mission-level analysis*, and the approach is commonly used by air component force planners. For instance, this approach is used to provide decision support for acquisition decisions on aircraft and weapons. In these trades, a suite of sensors, platforms, and weapons is modeled in the context of a scenario in which CONOPS, environmental factors, and adversary actions are represented. Key measures of performance and effectiveness are collected and compared to see which systems meet the warfighting goals. Companion analysis on the cost of these systems makes up a cost-effectiveness analysis.

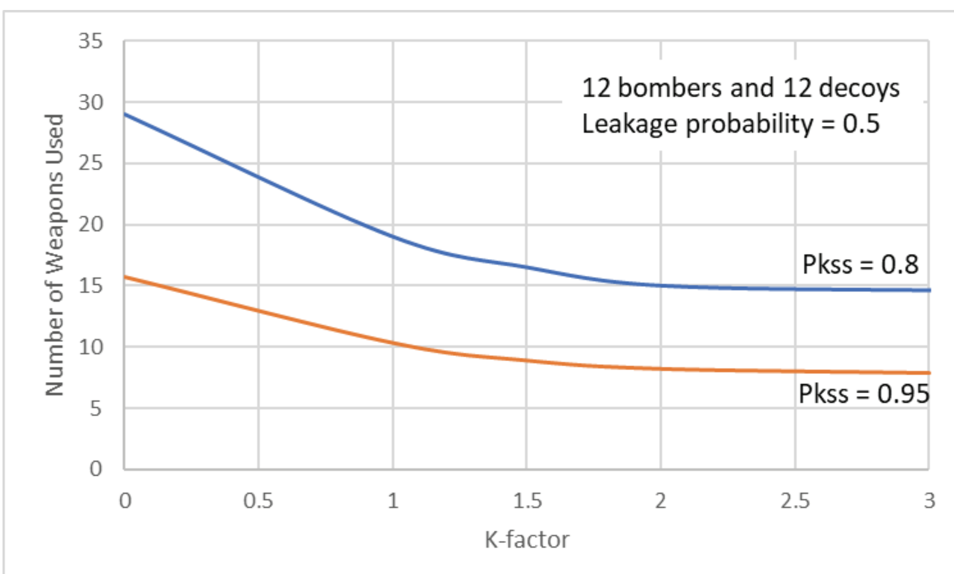
Selecting the appropriate analytic approach is important to best inform the acquisition decision. Models vary in level of detail and complexity, including engineering-level models that capture the physics of systems, engagement-level models that capture interactions of one system versus another one, mission-level models that represent many Blue systems versus many adversary systems, and campaign-level models that represent a major campaign. Campaign models, while weaker on details than higher-fidelity models, provide trade-off analysis in the context of war outcomes. A traditional force structure example might be two different proposed mixes of the numbers of fighter and bomber aircraft. A focused analysis on supporting enablers, such as space, can similarly feed input into a campaign model. For example, analysis on space-based ISR or SATCOM can provide measures of performance that are represented in a campaign model. Analysts could explore alternative space-based ISR architectures that support a fixed fighter and bomber force. In this way, campaign models allow enterprise-level trades that are tied to campaign outcomes. However, these trades are very complex, making direct linkage between one input (e.g., one space-based ISR architecture) and the campaign outcome difficult to connect. Mission models provide effectiveness trades for system capabilities and CONOPS. Direct linkage between system changes and mission outcomes is clearer than in campaign models. However, mission models do not capture enterprise-level trades, nor do they tie capabilities to campaign outcomes (because they are not modeled). Furthermore, they do not consider effects on other theaters.

Appendix C describes how the campaign outcome–guided mission-level analysis method can be applied to link SMA assessments to operations in other domains and enable SMA assessments spanning multiple mission areas. We apply the methodology to a notional trade-off analysis of weapons versus SMA for space-based ISR capabilities that are subject to counterspace attack. We provide a brief summary here. While the application we described is entirely notional and based upon notional data, it illustrates how the method can be used for a real-world application.

Consider a major campaign in which an adversary employs 12 long-range bombers to achieve its military objective, and in which campaign analysis shows that to meet Blue military objectives of halting the attack, Blue's initial attack needs to destroy six of the Red bombers within 12 hours from the start of the conflict and the remaining six in the following 12 hours. The adversary employs camouflage, concealment, and deception techniques, including the use of decoys. We assume a notional Red air base with a capacity of 50 possible locations for bombers and in which 12 bombers are stationed along with 12 decoys, i.e., 26 locations are vacant. The analysis compares two alternative space architectures that could provide ISR support to the mission, and those architectures are subject to counterspace attacks. We further assume for simplicity that a constellation of two satellites is sufficient to provide the minimum essential data needed to support the terrestrial mission. The decisionmaker needs to consider the trade-off in number of weapons needed to meet the operational objective versus the SMA of the two alternative space architectures.

Observe that this approach uses a campaign-level objective (i.e., halt the attack) to set a mission-level objective (i.e., destroy a percentage of Red bombers in a given amount of time). We used a variety of models to assess the kill chain for this notional example, including the Joint Munitions Effectiveness Manual (JMEM), to calculate the weapon's ability to destroy the target based on key parameters, such as weapon type and size, blast and fragmentation pattern, and target location error. We characterized the spaced-based ISR capability to distinguish bombers on bases from decoys in terms of the K-factor, which represents the discrimination capability of the space systems.[36] For instance, Figure 5.5 shows the number of weapons needed for the initial attack as a function of the K-factor, which ranges from 0 to 3 standard deviations, and the single-shot PK for the weapon.

Figure 5.4. (Notional) Number of Weapons Needed as a Function of K-Factor and Single-Shot Probability of Kill

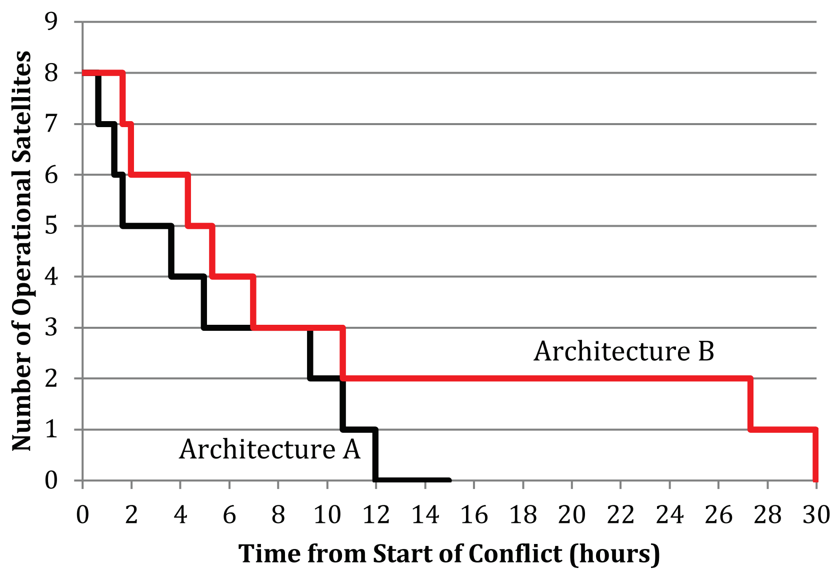


NOTE: Probability of kill is denoted as Pkss in this figure.

[36] The K-factor is the distance in standard deviations between the probability distribution functions of correct identification and false alarm.

Next, we employed a MATLAB model to assess the tactical drawdown curve associated with the two alternative space architectures subject to counterspace attack, using notional data. For instance, the two alternative space architectures may draw down at different rates because they employ different defensive measures. Figure 5.6 shows the drawdown curve we used in our assessment.

Figure 5.5. (Notional) Tactical Drawdown Curve for Two Alternative Space Architectures



We then combined results from these assessments to estimate the total number of weapons needed for the initial and follow-on attacks as functions of the SMA associated with each space capability. They are parameterized by the K-factor and the single-shot PK. The results are summarized in Table 5.2. Note that both Architectures A and B provide a similar level of support to the initial attack, while only Architecture B is able to support the follow-on attack. The follow-on attack results provided in Table 5.2 for Architecture A assume that no space support is provided and that all remaining possible bomber locations on the base need to be destroyed.

Observe that the results of the campaign outcome–guided mission-level analysis directly links an SMA assessment (the drawdown rates of two alternative space architectures subject to counterspace attack) to operations in another domain (the number of air-launched munitions needed to halt an attack).

Table 5.2. (Notional) Trade-Off in Weapons Needed to Meet Operational Objective Versus Space Architecture

K-Factor	Initial Attack (Within 12 Hours)		Follow-On Attack (12 to 24 Hours)		Total Number of Weapons	
	Architecture A	Architecture B	Architecture A	Architecture B	Architecture A	Architecture B
0	29/16	29/16	92/50	29/16	121/67	58/32
1	19/10	19/10	102/55	32/17	121/65	51/27
2	15/8	15/8	106/57	33/18	121/65	48/26
3	15/8	15/8	107/57	22/12	122/65	37/20

NOTE: Results are given for Pkss confidence interval of 0.8/0.95.

We recommend employing the campaign outcome–guided mission-level analysis methodology illustrated here to provide assessments of SMA linked to operations in other domains. While our example assessment illustrated how to conduct an assessment spanning a space and air mission, the same approach could be used to conduct an assessment spanning two space missions. This recommendation can help to address shortfalls S1 and S2.

6. Summary and Conclusions

Decisionmakers in the acquisition community need assessments characterizing the value of SMA to inform a variety of space investment decisions, such as architecture development, budget decisions, requirements development, and future concept development. These assessments can be used to balance SMA considerations with capability and cost. The operational community needs SMA assessments to support the development of OPLANs and tactics and to provide decision support for C2 and BMC2 of space operations.

A representative set of five existing analytic methods for assessing SMA was identified in this report:

- tactical drawdown
- operational drawdown
- static force structure comparison
- TVT
- WSDM

There are advantages and disadvantages to each. The methods and metrics used for SMA assessments need to be selected based on the specific decisionmaker needs, which is the case for similar assessments in other domains. We illustrated this point by describing two methods for assessing air base resilience. We also noted that the existing analytic methods lack adequate uncertainty analyses, which are needed to address an important shortfall.

The shortfalls are not unique to SMA assessments but are more severe than they are for similar assessments in other domains. Factors contributing to the severity include the relative newness of space as a warfighting domain, fragmentation of roles and responsibilities within the NSS community, and challenges associated with compartmentalization of data and information associated with SMA assessments. There are shortfalls (labeled S1 through S4) in

- (S1) established baseline and uncertainty bounds for inputs and assumptions needed for SMA assessments
- (S2) available methods for assessing social-behavioral aspects of SMA
- (S3) SMA assessments linking space to terrestrial warfighting operations
- (S4) SMA assessments spanning multiple mission areas.

USAF leadership should undertake the following three recommendations, which will require coordination with leadership across the NSS and which may help to address all of the shortfalls:

- Continue to fund and support the efforts undertaken by the JSWF, which is currently funded through FY 2020.[37]

[37] We note that subsequent to completion of our research, a Space Analysis Consortium was established in 2018. The purposes of the consortium are the "establishment of a coordinating body, with an accompanying process and

- Undertake an initiative to solve challenges associated with information-sharing. Specifically, we recommend establishing security constructs with terms of reference to facilitate the sharing of information.[38] Security classification guides should be reviewed and revised as needed to provide appropriate representation of capabilities at multiple security levels and access channels.
- Establish and fund an SMA Innovation Initiative to accelerate the closing of the shortfalls. A similar approach by DoD senior leaders has contributed to recent progress in wargaming, including the establishment of a "Defense Innovation Initiative" by Secretary of Defense Chuck Hagel in 2014, and the establishment of an innovation fund to "reinvigorate and expand" efforts across the community by Secretary of Defense Ash Carter in 2016 (Hagel, 2014; Carter, 2016).

The following additional recommendations for USAF leadership and analysts may help to address specific shortfalls:

- At a minimum, analysts should employ sensitivity analyses to help address shortfall S1. Leadership in the NSS analytic communities need to ensure that analysts have sufficient resources and scope to employ these methods. For more-complex SMA assessments, sensitivity analyses may be inadequate and more-sophisticated exploratory analysis methods may be needed, which leads us to the next recommendation.
- Employ analytic methods for decisionmaking under uncertainty, such as RDM. This recommendation can help to address shortfall S1.
- Characterize the role of space deterrence in SMA assessments and assess corner cases of space deterrence as applicable. Emerging models, such as the DSPAT and GIST, may help with assessments of space deterrence. This recommendation helps to address shortfall S2.
- Employ wargaming methods to identify adversary target priorities and rules of engagement regarding space warfare. This recommendation can help to address shortfalls S1 and S2.
- Employ campaign outcome–guided mission-level analysis methods to link SMA assessments to operations in other domains and the joint warfight. We illustrate this method in the report. The same approach can also be used to produce SMA assessments that span multiple space mission areas. This recommendation can help to address shortfalls S3 and S4.

The USAF will need to advocate for testing and evaluation of candidate analytical methods to support capability and concept development; architecture and force development; planning, programming and budgeting; development of OPLANs and tactics, techniques, and procedures (TTP). USAF analysts should track the use of RDM methods and modify them as needed.

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battle rhythm, to guide collaborative efforts across the space analytic community. The consortium will address space analytic gaps and needs, and support senior leadership decision-making and national security." (DoD, 2018b, p.6). This consortium could be the follow-on to the JSWF.

[38] For instance, the Air Dominance Initiative provided a security construct for collaboration and information-sharing by DARPA, the USAF, and the Navy (McLeary, 2015; Defense Science Board, 2016). Also see Alkire (2018, Appendix D) for historical examples.

Assessing the need for a Space Force or options for implementing it were not within the scope of this project. However, some reports have suggested that reducing fragmentation of the NSS community may be an objective for a Space Force (Hildreth et al., 2018, paragraph 1). Reducing fragmentation could contribute to addressing shortfalls S1 and S4. However, space and air missions are currently integrated within the USAF, so it could be argued that creation of a separate Space Force would increase fragmentation.

Appendix A. Example Application of an RDM Methodology to an SMA Assessment

Motivation

As described in Chapter 4, there is a shortfall in established baseline and uncertainty bounds for inputs and assumptions needed for SMA assessments.

In this appendix, we describe how RDM methods can help to address this shortfall.

For SMA assessments, uncertainties are embedded in IC estimates of enemy space and counterspace orders of battle and capabilities; in defense-planning scenarios used for conducting assessments; in the service life of fielded U.S. systems; in the performance of the DoD acquisition system to deliver replacements or upgrades; in the performance of fielded U.S. weapon systems in tested or untested conditions or against unforeseen threats; among dozens of other factors. In some cases, constraints imposed by classification barriers inhibit information-sharing in ways that create uncertainties about programs, capabilities, or intelligence for uncleared analysts and decisionmakers.

To the extent that DoD decisions hinge on judgments about these or other factors, DoD decisionmakers confront several risks with regard to the way uncertainty is treated. For one, paralysis could result if analysts delay assessments until adjudicated sets of assumptions are approved and made available to resolve the unknowns. The semistructured interviews conducted as part of this research revealed at least one example of such "paralysis in analysis" in the space force planning community. Perhaps of more serious concern, COAs could be pursued based on faulty assumptions. Thus, the need to competently cope with uncertainty is of paramount importance.

The challenge of decisionmaking under uncertainty is not unique to space nor to defense planning. An entire scientific discipline and community is organized around developing and applying methodologies and tools for this purpose. A thorough review of the broad literature on decisionmaking uncertainty is both beyond the scope of this report and beside the point. The good news is that solutions are afoot.

A Traditional Approach: Scenario-Based Planning

Because uncertainty is part and parcel of defense planning, it should not be surprising that approaches have been institutionalized. One approach, scenario-based planning, is pervasive within DoD. Although it would be misleading to say that every analysis conducted in or by DoD adopts a scenario-based approach (indeed, approaches have evolved over the years), scenario-based planning is currently represented in the mainline DoD force planning process, most recently called Support to Strategic Analysis. The process involves a sequence of three basic steps.

The first step is to identify and articulate a set of scenarios. Formally, these scenarios are represented by Defense Planning Scenarios and Integrated Security Constructs that the Office of the Under Secretary of Defense for Policy develops in coordination with OSD CAPE, the staff supporting the Joint Chiefs of Staff, and the military departments. The scenarios are generally representative of the Presidential Contingency Planning Guidance and the missions assigned to the military through the U.S. defense strategy. The scenarios are posited sometime in the future—generally five years out—to align derived assessments with the PPB processes that develop the Future Years Defense Program. The scenarios codify a set of putatively representative assumptions about situations in which the U.S. military should be prepared to deter adversary aggression and, if deterrence fails, defeat or deny adversary objectives. Various uncertainties are resolved by making assumptions about specific adversaries, U.S. and adversary wartime objectives, warning times (including a road-to-war), rules of engagement, and access to bases in and overflight of partner territory.

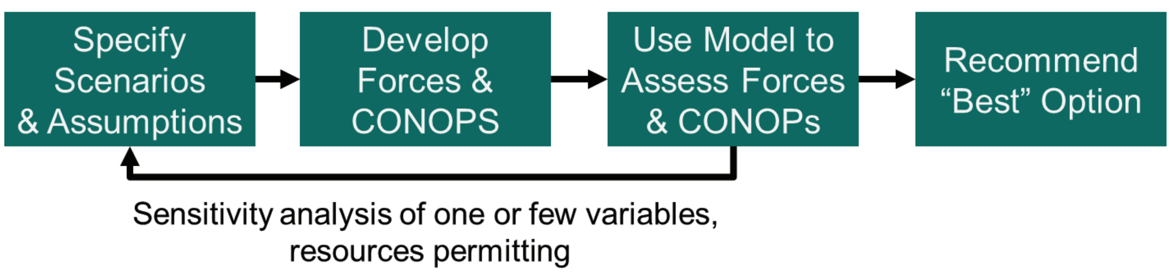
The second step involves elaborating the scenarios from the first step with baseline forces and CONOPS that the United States and adversaries will employ in the scenarios. Among other factors, the forces and CONOPS articulate expectations on force flow and allocation, mission assignments, campaign phasing, force bed-downs, contributions of allies and partners, and other factors. Practically speaking, this step culminates in a several-hundred-page document developed by the Joint Staff in coordination with the rest of DoD, including Office of the Under Secretary of Defense for Policy, OSD CAPE, the IC, and the Service departments. The document and associated databases reflect the judgment of military planners informed by the accessible intelligence assessments and DoD's consensus of U.S. and adversary forces and CONOPS in the chosen scenarios.

The last step is assessment. Assessments include sufficiency analyses (i.e., quantitative comparisons of the supply of and demands for forces) and proficiency analyses (i.e., modeling and analysis at the engagement, mission, and campaign levels). These assessments are generally conducted by using the scenarios, forces, and CONOPS developed in the prior steps. Often, additional assumptions are introduced to reconcile uncertainties about the performance of specific weapon systems (e.g., probability of detection, kill, or survivability), environmental conditions (e.g., weather, visibility), TTP, and human factors (e.g., the proficiency of the operators). On the basis of these assessments, conclusions are drawn to form a baseline assessment of the programmed force, and to recommend potential enhancements.

This scenario-based approach emphasizes depth of analysis by focusing on detailed analysis of selected scenarios and assumptions developed through a linear scenario development and assessment process. From the perspective of this report, it is worth observing how the approach treats uncertainty.

Generally speaking, the scenario-based approach resolves uncertainties by carefully adjudicating assumptions and then conducting analysis, formulating conclusions and recommendations, and making decisions on the basis of those assumptions. (This process is responsible for the "Predict then Act" moniker for scenario-based planning.) Sensitivity analyses are widely recognized by practitioners of scenario-based planning to be necessary to ensure that any decisions are not unduly dependent on input assumptions. This necessity puts the burden on the decisionmakers or analysts to identify the assumptions that are most worthy of sensitivity analysis; it also requires resources and time at the end of an assessment, often when decisionmakers eagerly await final products. Some observers have argued, on the basis of these observations and others, that scenario-based force planning does not work as well in situations in which there are many uncertainties, or when the uncertainties are not easily characterized by probabilities. Such conditions do not lend themselves to easy (or reliable) parametric analysis (Davis, 2016). Over time, DoD's implementation of this process has come to include a greater number and variety of scenarios, in part addressing some of the concerns (Khalilzad and Ochmanek, 1997). The basic steps of scenario-based planning are depicted in Figure A.1.

Figure A.1. Scenario-Based Planning



An Alternative Approach: RDM

Modern advances in decision science, modeling and simulation, and computing have spawned new approaches to decisionmaking under deep uncertainty. The RDM methodology is one approach specifically designed to embrace the kinds of uncertainty found in force planning.[39] The basic concept is straightforward: Rather than optimize outcomes over a best-guess future (or

[39] A precursor to RDM methodology referred to exploration of "scenario space" in defense analysis (Davis, 1994; Davis, 2014). Davis urged moving away from "point scenarios" as the basis for defense planning toward capabilities analysis that sought to assure the capability to handle as wide a portion of scenario space as possible within a budget. He excoriated optimization around a point case in favor of such uncertainty-sensitive planning. A largely parallel effort proceeded independently to address such issues as climate change, as later described in Lempert and Collins (2007). Today, the ideas and methods from both early approaches are subsumed by what RAND and international analysis groups refer to as RDM. RDM methods have been used in dozens of studies in diverse areas (see RAND Corporation, undated) and has spawned the international Society for Decision Making Under Deep Uncertainty. That research has also generated several powerful analytic tools.

the somewhat more sophisticated but related approach of optimizing over a curated set of several chosen scenarios), RDM envisions searching for policy options that are "robust" across a range of potential scenarios. Rather than requiring prior agreement on assumptions as an input, RDM provides a protocol for identifying short-term COAs that meet prescribed objectives across multiple futures. The robustness criteria does not require maximizing goals (which are inherently tuned to a specific set of scenarios) but instead seeks to achieve *minimal* criteria for satisfactory outcomes within measures defined by decisionmakers. This view aligns with Nobel laureate economist Herbert Simon's observation that rather than maximizing behavior postulated in economic theory, businesses will seek to "satisfice" (Simon, 1959)—that is, in the presence of difficult-to-characterize uncertainties, businesses will take COAs designed to achieve "good" results across a range of potential future conditions. This strategy contrasts with more brittle optimizing strategies that might well result in disaster when met with a different reality than had been presupposed. RDM has proven valuable to policymakers in a range of settings (RAND Corporation, undated).

RDM follows a different sequence of steps. The first is to start at what was the end of the process of scenario-based planning: the decision. That is, instead of starting by identifying a set of scenarios, we instead ask questions about end objectives and the options available to meet those objectives. In the context of force planning, the options may pertain to alternative force structures, capabilities, or CONOPS.

Second, RDM requires identifying the factors that that may influence the decision. The factors group into one of four categories:

- key variables and potential configurations of those variables, reflecting uncertainty
- exogenous key variables
- suppositions regarding the causal mechanisms between key variables and decisions, leading to outcomes
- different metrics used to characterize those outcomes as good or bad.

Third, RDM calls for a strategy of performing a large number of compound computational experiments to test the implications of alternative assumptions regarding uncertainties by applying options identified in the first step against the many cases generated by the combinations of different assumptions and then assessing outcomes across the full range of measures identified in the second step. This competition among different options against a level playing field of many cases is itself an iterative process, with learning and refinement to both the set of alternative futures and the composition of the options. The computational experiments rely on a simple, transparent, and fast-running model to facilitate rapid and wide-scale exploration of the scenario space. The availability of such a model, or feasibility of developing one, naturally depends on the decision.

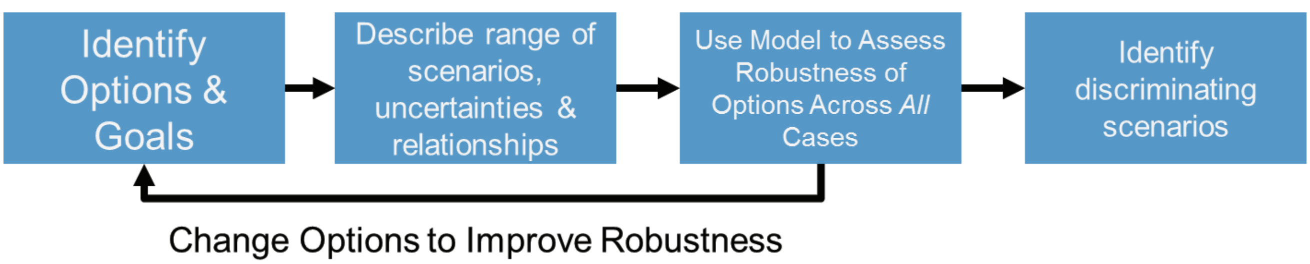
The resulting database derived from the trials of the alternatives may then be explored for those cases in which each option failed to meet the minimum standards set for one or more outcome metrics. We may then use data mining techniques to understand what is systematic across the failure modes for each option and identify the factors that discriminate the options. There may be many cases in which all options succeed or fail to meet the minimum goals; RDM refers to these "scenarios" as unhelpful for discriminating the options under consideration. But there will likely be other cases in which the options diverge in the success or failure of goals, revealing themselves as discriminating factors that should attract decisionmaker attention. Decisionmakers may then ask whether these discriminating cases are situations in which they should accept or mitigate risk. The ability to focus attention on the uncertainties that should affect the decision—the uncertainties that matter, so to speak—is a virtue of RDM.

With this approach, we will have completed a full inversion: Rather than beginning with selected scenarios and then conducting the assessment, we instead used a process to discover and develop increasingly robust force plans and to derive scenarios given our policy goals that may stress the candidate force plans.

Inherent in this process is the ability to modify or even hybridize options to reduce vulnerability to the stressful scenarios that analysis has identified and repeat the process until vulnerability can be reduced no further. This ability derives from the conscious choice to shift from an analytical strategy of enhancing predictive power to one instead pursuing robustness across plausible futures. This stance then allows us to characterize uncertainties not by probabilities but rather by the effect of the uncertainties on our choices and how we decide among those choices.

Figure A.2 provides a depiction of the basic steps in RDM. A more fulsome summary of the method of RDM can be found online (RAND Corporation, 2013, and RAND Corporation, undated).

Figure A.2. Robust Decisionmaking Methodology



RDM Example

Identifying Goals: Improving Space Mission Assurance

The first step in the example RDM analysis is to identify options and goals. The principle goal for this OORF example is improving SMA, either by *improving the resiliency of the enterprise space architecture* or by *improving the survivability of individual satellites.* At this point, it is useful to consider a viable metric to assess the baseline capability of our space system, and with which we can measure the enhanced mission assurance achieved with a fielded OORF capability. With consideration for the basic mechanism by which OORF contributes, we chose to develop a metric deemed Aggregate Life Remaining (ALR). This basic, mission-agnostic measure of interest allows for a quantifiable, deterministic assessment of the contribution of the OORF in a contested environment. There are three important assumptions inherent to this metric:

- The constellation is fully deployed prior to hostile engagement.
- Elements of the constellation are deployed at regular intervals.
- Each element of the architecture ages equally and contributes equally to the mission.

This metric has the added benefit of allowing for enterprise-level trade-offs and roll-ups. Because the added fuel equates to longer mission availability, the value of one year's capability can be determined: Time is literally money. Furthermore, by summing the combat losses and potential OORF contributions to diverse systems (e.g., GPS, MILSATCOM platforms, SBIRS), a truly enterprise metric emerges without the need to equate disparate combat contributions.

The initial ALR (ALR_i) for a constellation is mathematically defined as

$$ALR_i = \sum_{j=1}^{N} \frac{j}{N} \times L$$

where

- L = satellite design life
- N = number of satellites in orbit.

This equation implies that each satellite degrades linearly, and that the newest (*Nth*) satellite has a full design life remaining, while the oldest (j = 1) satellite will require replacement next. Again, ALR is our measure of mission performance, however this is not our resilience metric for assessing SMA. First, we must represent the postattack or postrefueling ALR (ALR_f):

$$ALR_f = ALR_i - Life\ Remain_{SatsKilled} - Life\ Remain_{SatsEvaded,no\ refuel} + Life\ Added_{refueled}\ .$$

With these two quantities defined, we turn to the PDSA Mission Assurance Assessment Framework (Stanton and Zondervan, 2017) for guidance to quantify resilience. Stanton and Zondervan describe several methods with increasing complexity for defining the resilience metric; we adopt the most basic, which is simply the ratio of final capacity over initial capacity. That is,

$$Resilience\ ratio = \frac{ALR_f}{ALR_i}\ .$$

Now we posit two mechanisms for OORF to improve the SMA of the enterprise space architecture:

- *Reconstitution.* In principle, an OORF capability could be used to reactivate previously retired satellites, thereby reconstituting satellites damaged or destroyed in wartime.
- *Proliferation*. An OORF capability could increase the total number of satellites in orbit if the refueling had the effect of extending the service life of satellites that would otherwise be retired.

We posit two mechanisms for improving the SMA associated with individual satellites:

- *Resiliency via protection*. An ability to refuel a satellite may allow satellites to recover fuel expended during evasive maneuvers conducted *after* a real or simulated ASAT weapon launch. If the satellite's fuel supply constrained the ability to exercise or execute such maneuvers (e.g., for fear of significantly reducing service life), OORF could create an opportunity to improve protection by relaxing that constraint.
- *Resiliency via deception.* An ability to refuel a satellite may allow satellites to recover fuel expended during evasive maneuvers *prior* to ASAT weapon launch to deceive adversary SSA capabilities. If conducted during peacetime, such maneuvers could persistently degrade an adversary's confidence in its SSA. If conducted in wartime, such maneuvers could frustrate an adversary's ability to target satellites for kinetic or nonkinetic attack. If the satellite's fuel supply constrained the ability to execute such maneuvers, OORF could create an opportunity to improve resiliency by relaxing that constraint.

It is important to note here that OORF does not directly mitigate the threat of an ASAT attack on a satellite; the refueler is not presumed to respond fast enough to add fuel prior to a hostile engagement. Rather, the OORF capability serves to backfill the fuel previously onboard, which was used to survive by maneuver.

Identifying Options

An early step in the example RDM is being explicit about the options under consideration to achieve the goals. For purposes of the example, we posit an OORF capability characterized as follows: An orbit refueling capability that can respond in a matter of minutes to hours for satellites in geosynchronous orbit, or hours to one to two days for satellites in a supersynchronous "graveyard" orbit. This hypothetical capability is presumed to be responsive, not proactive, as a means of restoring on-orbit capability. For satellites that have depleted existing fuel reserves in a successful effort to avoid an attack, the OORF satellites would restore some amount of fuel lifetime reserve. When a satellite has been destroyed by hostile attack, the OORF system would rendezvous with previously disposed-of spacecraft. The OORF system would assume the navigation and propulsion system duties of the retired satellite and bring it back to an operational capability.

For purposes of this decision, we will assume the OORF capability as described is technologically feasible. The primary decision is how to design and employ an OORF force structure by scoping the mission requirements. We posit three broad COAs:

- Baseline: no investment in OORF
- COA 1: invest in a large number of refueling platforms (called TankerSats)
- COA 2: invest in high-capacity refueling platforms.

The reader may notice that many parameters are unspecified—both in capability and performance—that one might expect to be necessary. This is a key point: We will treat these factors as uncertainties (not levers) in this prototype, because, from the perspective of the decisionmaker at this early stage of the development, the technological and programmatic risk means the future capability is largely uncertain. These options are specified in Table A.1.

Table A.1. OORF Capacity Options (or Levers)

Factor	Definition	Potential Configurations
TankerSats fielded	Number of OORF platforms	0–46
Life extension, GEO	Percentage of design life restored	25–75%
Life extension, SuperSync	Percentage of design life restored	25–75%

Identifying Exogenous Factors and Relationships

RDM requires describing the range of exogenous factors that may affect the options and goals, as well as the relationships for their interaction. Table A.2 summarizes the range of factors and possible configurations that we identified and explored in our example.

Table A.2. Exogenous Factors

Category	Factor	Definition	Potential Configurations
Scenario	Enemy	Which state is posing the threat	N/A—represented through counterspace order of battle and capability
	Warning	How much time is available to alert operators of a potential attack in space	0–6 hours
	Deterrence	Whether adversary will be deterred from attacking certain “protected” satellites	0 = Yes 1 = No
Enemy counterspace availabilities	Order of battle	Number of ASATs in inventory	0–46
	Capability	Time of flight PK	3–6 hours 0.2–0.9
Enemy counterspace CONOPS	Attack strategy (Shot Doctrine)	Whether targets are attacked with one ASAT or two ASATs	1–2

Category	Factor	Definition	Potential Configurations
U.S. space capabilities[a]	Order of battle	Number of satellites in the constellation	4–12
	Service life	Planned service life of satellites in the constellation	6–12 years
	Reconstitution capability	Number of satellites available in graveyard orbit	0–5
	Other resiliency mitigations	Probability that an attack is mitigated	0.2–0.9
U.S. space CONOPS	Response time, GEO	Time until rendezvous and refuel	3–12 hours
	Response time, SuperSync	Time until rendezvous, refuel, and transfer to GEO	12–36 hours

[a] At some level of OSD, the confluence of decisionmaking may deem U.S. space capabilities and U.S. space CONOPS as internal levers and not exogenous. However, for the purpose of this prototype, we are assuming that the OORF decisionmaker does not directly control these conditions.

In addition to identifying exogenous factors, we must articulate the relationships among these factors. There are several relationships that we represent mathematically. The first relationship is the outcome of an ASAT attack on an individual satellite. As discussed elsewhere in this report, the USAF and OSD have begun to adopt a mathematical model for system survivability that is well-suited to our present task: the TVT model (Stanton and Zondervan, 2017). We modified and applied here an adaptation of the TVT model that was specifically tailored to exploring OORF. The probability of survival for each attack within the model is calculated similarly to the approach described by Stanton and Zondervan (2017), which details the TVT model. The full TVT application is represented mathematically by the following equation:

$$P_S = \prod_{\tau=1}^{n_T} \left(1 - [P_k]_\tau \left(\prod_{\mu=1}^{n_M} 1 - [P_m]_{\tau,\mu} \right) \right)$$

where

- n_T = the number of different threats
- n_M = the number of different mitigators.

The model can accommodate multiple threats with variable performance as well as multiple threat-specific mitigation techniques in response to those threats. For the purpose of this OORF prototype, we used a single threat with a constant PK (P_k) and a steady-state probability of mitigation value (P_m) as well. However, the arsenal of that single threat grows with time in our model. Not shown here, but equally valid, is that the probability of survival (P_s) can also vary with time if either the P_k or P_m values are time-variant.

Because we assess the performance of the system against multiple shot doctrines (a single ASAT shot per satellite as well as two shots per satellite), we apply the above P_s value directly in an engagement or use it as the basis for the probability of surviving two independent events. This application results in different drawdown rates for the two doctrines against a given order of battle.

A second relationship is the connection between individual satellites and the enterprise, which is described by the ALR metric discussed earlier in this appendix.

A third relationship is the connection between OORF platforms and satellites that have successfully evaded an attack and require refueling. We assume that OORF would recoup the lesser of the following options:

- The amount of fuel previously onboard that was consumed by evasive maneuvers. This refueling resets the service life to its premaneuver state.
- The predefined amount of refueling capacity maintained by each TankerSat (expressed as a percentage of the original design life).

The time required to rendezvous and refuel is randomly drawn from a selection of astrodynamics calculations. Our model accounts for the fielded and expended numbers of tankers previously exploited. It is feasible to have more satellites killed than can be refueled at a particular time. In that case, some satellites may have zero ALR, even though they may technically still be mission-capable. This number of satellites refueled is expressed by the following equation:

$$Satellites_{Refueled} = \min(TankerSats_{Available}, Satellites_{RunNotKilled}) .$$

The fourth relationship is the connection between OORF and reconstituted satellites. We assume that for the return of disposed satellites, some reasonable doctrinal changes would have been made previously. Current procedures call for satellites to be configured in a safe mode prior to disposal, which would render them all but unusable in the future. However, changes to the nature of military space operations may merit further consideration. If we assume these changes to have been made, the relationship to determine how many reconstituted satellites are in play is elementary; it is simply equal to the constraining factor among all the needed elements. Mathematically:

$$Satellites_{Reconst} = \min(Satellites_{Disposed}, TankerSats_{Available}, Satellites_{Killed}) .$$

This relationship ensures that there is a need for a reconstituted platform (only those satellites killed are replaced) and also that the resources (that is, a tanker and a disposed platform) are available. We recognize that the operational complexity of such a maneuver would be high initially.

However, rendezvous and proximity operations have already begun to promote the feasibility of such operations. Additionally, our model simply assigns a random value for the time that would be required to complete this operation, instead of a more complex determination based on phasing orbits, rendezvous, and repositioning back into the geosynchronous belt. The reconstituted satellite is defined to have the same amount of life remaining as the satellite which it essentially replaced. This definition ensures that we are not overloading the final ALR.

Identifying Measures

RDM requires specifying measures that instantiate the goals from the first step. Here we posit three measures (see Table A.3). We will consider the OORF investment decision from the perspective of each individual measure and from the perspective of the collection of measures. These measures emerge from the model output, define a "successful" future state, and define some facet of military utility enhanced by the OORF system when each measure is compared with the same scenario absent OORF.

Table A.3. Measures

Measure	Definition	Minimum Goal
Minimum satellites available in a campaign	The minimum number of satellites available in the course of a 168-hour campaign	Greater than *N* satellites in U.S. space order of battle, where *N* is a parameter greater than zero
Postconflict ALR (ALR_f)	The number of design-life years available at the end of a campaign enterprisewide, after all possible reconstitution has occurred	Greater than *N*% of ALR_f without refueling, where *N* is a parameter we vary from 50–90%
Resilience ratio	The ratio of enterprisewide design-life years available postconflict over design-life years available preconflict	Greater than *N*% of resilience ratio when OORF is absent, where *N* is a parameter we vary from 50–90%

A Simulation Model for Exploratory Analysis[40]

A next step is to develop a simple, transparent simulation model that implements the relationships established in the previous section, providing a basis for computing measures as a function of levers and exogenous factors.

Our spreadsheet-based engagement simulator is designed to examine a straightforward interaction between a mixed-capability satellite constellation and threat systems aligned against those satellites. In addition, the simulator considers the potential for threat mitigation from early warning of attacks. The premise for including this latter consideration is that with added attack

[40] In describing exploratory analysis methods, we recognize some alternatives. Alternative 1 is that RDM leans on the computation to "discover" the important scenarios with data mining. Alternative 2 emphasizes smart-analyst thinking to identify regions of scenario space that pose different challenges. It then identifies test cases for each (and parametric testing around each), and uses computation to sharpen this problem structuring and to test options. As with RDM, it seeks strategies that are robust, although it uses the terminology of seeking "FARness," or strategies that are flexible, adaptive, and robust. In this usage, flexibility allows change of mission, adaptiveness allows dealing with varied circumstances, and robustness refers to withstanding shocks. A simplified version of Alternative 2 is to recognize the most fundamentally different scenario classes quickly up front (they may be glaringly obvious) and have corresponding bases and excursions. In some cases, this approach can be straightforward and not appear so exotic as Alternatives 1 or 2.

warning time, a satellite could begin to maneuver out of the threat interceptor's range (or field of view) in ways that would reduce the PK by the threat system.

The parameter values used within the simulator are based on astrodynamics calculations of orbital maneuver. These calculations are embedded in such values as the range of fly-out times for a terrestrial-based ("direct-ascent") attack system and orbital transfer times for orbit-to-orbit maneuvers. The simulation also has several distinctive features to determine the resilience of the mixed constellation. The simulation takes 15 input variables, which characterize the exogenous factors and internal levers discussed previously as presumably important to an OORF system decision. The simulation also considers two adversary attack philosophies: a one-shot doctrine per satellite and a two-shot doctrine in which two weapons are immediately deployed against a single Blue asset. The simulation can also accommodate a third shot doctrine of shoot-look-shoot, although this doctrine is evaluated only through Monte Carlo analysis instead of deterministically, in contrast to the other doctrines. Regardless of shot doctrine, each satellite is engaged individually and sequentially. The simulator evaluates—on an hour-by-hour basis for 168 hours—the expected value for the number of satellites remaining from the total order of battle. The number remaining consists of the original order of battle less the number of successful ASAT attacks and incremented by the number of reconstituted satellites (when OORF is available). Because this simulator also includes a basic deterrence parameter, the total number of satellites that may be engaged in hostilities may not be assumed to be the full order of battle. In essence, some satellites are defended by deterrence.

The goal for the example is to assess the potential for improving SMA through OORF. In order to do so, it was necessary to assess SMA. We adopt the TVT approach (Stanton and Zondervan, 2017). At this approach's most basic level, the measure of some capability of an architecture prior to a hostile engagement is compared with the residual capability after the engagement. With an eye toward assessing the benefits of OORF, the measure of interest here is the useful life remaining of an on-orbit constellation. This measure has utility for multiple reasons. First, the measure is transferable within a space enterprise because it is mission agnostic. Constellations of different size and purpose can be compared, and decisions among them can be made. However, there are several assumptions and caveats. As noted in Stanton and Zondervan (2017), simply measuring pre- and postattack capability is not always an accurate assessment. For example, constellations may have on-orbit spares in place to quickly respond to anomalies. These spares may be kept in a lower state of readiness and may also represent capacity over and above the required minimum. In these cases, the loss of a satellite during an engagement still would not reduce the available capacity below 100 percent of the needed capacity even though losses would be taken. Another assumption used here to reduce mathematical complexity is that of a linear degradation in the remaining life of a satellite, based on the order in which it was launched. For many reasons, this assumption may be invalid. For example, satellites may have been maneuvered excessively.

Conduct Scenario Discovery

Our approach to scenario discovery relies on a "wrapper" application written in Python that runs the spreadsheet-based engagement simulator in an iterative fashion. The wrapper uses a Latin hypercube sampling technique to create sets of near-random values for each of our parameters, feeds the parameters into the engagement simulator, and then records the output variables of the simulator back into the wrapper application.[41] Each set of parameters fed into the engagement simulator can be considered a potential future *state of the world* (SOW) or scenario. It is important to note that we make no prejudgment about the likelihood of or preference for each SOW, only that it is feasible given the range of values we defined for each variable. This relates to our original premise that we have no clear vision of what appropriate scenarios or assumptions may be. We simply run possible SOWs through our models and observe whether the result is favorable (successful) as defined by the measures listed in Table A.3. Having run this code for 10,000 unique scenarios and tracking the outcomes of each, we can gain insight through observation of the range of values for each parameter that led to a successful outcome. Table A.4 shows the output for our 10,000 scenarios in terms of our measures. Note that we analyzed each case against both a one-shot and two-shot doctrine by the adversary.

Table A.4. Success Cases for Measures of Interest

Measures	Minimum Goals	Successful SOWs
	Adversary One-Shot Doctrine	
1. Minimum satellites available in a campaign	The minimum number of satellites available is higher by two or more with OORF than without it	2,390 out of 10,000
2. Postconflict ALR, ALR_f	The ALR_f at the end of a campaign is 50% higher or more with OORF than without OORF	6,622 out of 10,000
3. Resilience ratio	The resilience ratio is improved by 25% or more with OORF than without OORF	7,582 out of 10,000
	Adversary Two-Shot Doctrine	
4. Minimum satellites available in a campaign	The minimum number of satellites available is higher by 2 or more with OORF than without it	3,225 out of 10,000
5. Postconflict ALR, ALR_f	The ALR_f at the end of a campaign is 50% higher or more with OORF than without OORF	8,222 out of 10,000
6. Resilience ratio	The resilience ratio is improved by 25% or more with OORF than without OORF	7,375 out of 10,000

From this table, we observe our first major finding of the RDM example to scenario analysis.

[41] The Latin hypercube sampling technique is referred to as "near-random" because this methodology ensures balanced representation across the range of values for each parameter. As a result, there is a more uniform distribution across bins of equal likelihood than one would observe with a truly random sampling technique.

Finding 1: RDM analysis aids in setting rigorous goals for measures of interest. Table A.4 shows the number of successful runs out of 10,000 for each of our minimum goals. Note that for four of our six measures, well over 50 percent of the cases we ran met the goal. Only measures 1 and 4, at 23.9 percent and 32.3 percent, respectively, established challenging criteria in which more scenarios failed than succeeded. This indicates that for the other four measures, more-rigorous goals should have been set to identify more discerning scenarios.

Next, we will look more in-depth at the ranges of parameters for measure 1 in Table A.4. What follows could be applied for each measure described earlier. In fact, if the measures are deemed important at the outset, what follows should occur for all six measures. Recall from Table A.1 and Table A.2 that we described a range of input values based on either astrodynamics or historical constellation management to inform the scenario analysis. Those ranges are reproduced here in the "Input Range" column of Table A.5. The "Findings Range" column of Table A.5 is highlighted to show the refined values based on our RDM scenario discovery analysis. This column shows the range of values for each variable in the 2,390 successful scenarios when indexed to measure 1. Two additional findings emerge from this table.

Table A.5. Scenario Discovery Output Table, Measure 1

Variable	Units	Input Range	Findings Range
Wideband constellation	Satellites	4–12	**5–12**
Disposed-of wideband satellites	Satellites	0–5	**1–5**
Wideband design life	Years	6–12	**7–12**
Protected SATCOM constellation	Satellites	4–12	**4–10**
Disposed-of PSC satellites	Satellites	0–5	**3–5**
PSC design life	Years	6–12	6–12
Deterrence	Yes/No	0–1	0–1
PK	Percentage	20–90%	**20–87%**
Threat attack time to GEO	Hours	3–6	3–6
TankerSat response time to GEO	Hours	3–12	3–12
TankerSat response time to supersynchronous orbit	Hours	12–36	12–36
TankerSat life extension at GEO	Percentage of design life	25–75%	**41–75%**
TankerSat life extension at supersynchronous orbit	Percentage of design life	25–75%	**32–75%**
Attack warning time	Hours	0–6	0–6
PM	Percentage	20–90%	**20–77%**

Finding 2: RDM analysis clarifies variables of relevance. Recall that we began with 15 variables of interest to feed into our model. Based on the values in Table A.5, we can see that only nine variables (in bold lettering) discriminate in any way. For the other six variables, successful scenarios were found across the full spectrum of values presented in the "Input Range" column. As a result, that variable can be set at any value and success is still possible at the level of the minimum goal given for that measure.

Finding 3: RDM analysis highlights thresholds and ranges of success for variables of relevance. Building on Finding 2, we can see that the nine variables of relevance provide further insight. Once again, the "Findings Range" column of Table A.5 represents the range of values present in the successful cases. Interpreted differently, no successful scenario—as defined by measure 1—had a value outside of that range for a given variable. This may help to considerably tighten the potential scenario-definition space. If these are considered thresholds of success, they can prevent over- or underdesign of the future system. For exogenous factors, they may represent warning signs suggesting measured success may become difficult or impossible.

Refine COA and Iterate

The next step for an RDM analysis is to refine COAs on the basis of scenario discovery, with a goal of improving robustness. The example as applied here does not require iteration, as it is simply a proof-of-concept effort. Recall that we had three COAs for consideration:

- Baseline: no investment in OORF
- COA 1: invest in a large number of refueling platforms (TankerSats)
- COA 2: invest in high-capacity refueling platforms.

It is still instructive to briefly reconsider our original COAs even without the intent of a full iteration of the analysis. Based on the RDM analysis presented earlier in this chapter, many scenarios exist in which we can improve upon the baseline (and therefore the SMA) of our system with the addition of OORF. With regard to COA 1, the RDM analysis indicates that the number of disposed satellites available for reconstitution is a variable of relevance. Therefore, it should be viewed as a pacing function with regard to the number of refueling platforms developed. In other words, there is a limit to the top-end number of platforms that should be considered. Finally, the RDM analysis contributes directly to refinement of COA 2. Note that in Table A.5, both the *TankerSat Life Extension at GEO* and the *TankerSat Life Extension at Super-sync* variables are relevant. Additionally, the variables have a narrower range of success than originally posited. This analysis begins to validate the COA 2 approach of high-capacity refueling platforms, though further analysis is certainly warranted.

In the course of developing this example, we discovered what could be considered a negative takeaway of the RDM process. Initially, our engagement simulation model and RDM analysis included some 25 distinct variables, which represented acquisition inputs (unique initial operational capability and full operational capability dates as well as fielding rates for threat systems and tankers). These variables increased the computational load for sufficiently deep analysis of the trade space. But more importantly, we found that the analysis rarely resulted in much refinement to our initial ranges for the levers and factors. Upon investigation, we discovered that the solution space for successful scenarios was essentially underconstrained; too many successful combinations existed to discriminate from. To address this, we chose to narrow the prototype to only address operational performance parameters. In support of a true acquisition decision such as the one outlined here, our recommendation would be to run two distinct RDM efforts: one focused on refinement of the acquisition factors and a separate effort focused on operational capabilities. If time and resources then permitted, the two could be integrated for further insights.

Summary

In this appendix, we described RDM as one approach to addressing uncertainty in SMA assessments. We developed an example application of RDM to a plausible but fictitious decision regarding investments in OORF for SMA. The example provides a proof-of-concept demonstration of the approach.

Appendix B. Sensitivity Analysis with Application to SMA Assessments

As discussed in Chapter 4, one of the key shortfalls is established baseline and uncertainty bounds for inputs and assumptions needed for SMA assessments. Uncertainty in many of these input variables exists because of intelligence gaps, a lack of empirical data (e.g., capabilities of a weapon system), inherent variations in input variables (e.g., performance degradation of a weapon system over time), or because the input variable may simply be inherently uncertain (e.g., how threats arise and evolve over time). One approach to deal with uncertainties in inputs or assumptions is to evaluate how such uncertainties affect SMA assessment results; that is, conduct a sensitivity analysis.

In this appendix, we examine various sensitivity analysis methods and practices that may be suitable for some SMA assessments and decisionmaking. However, the sensitivity analyses described here are useful for evaluating excursions of a small number of variables in the vicinity of some suitable pivot point.[42] As a result, they have limited utility for assessing uncertainty. For more complex SMA evaluations, methods specifically designed for decisionmaking under uncertainty should be employed, such as the RDM methodology described in Appendix A.

This appendix also discusses several visualization methods that may be suitable for communicating uncertainty and sensitivities. Many of the techniques described in this appendix, including visualization techniques, have applications beyond sensitivity analysis.

Background

Sensitivity analysis provides insights into how these uncertainties affect SMA assessments and resulting COAs. It can help overcome the challenges associated with a lack of established baseline and uncertainty bounds for inputs and assumptions in a variety of ways. For instance, it can

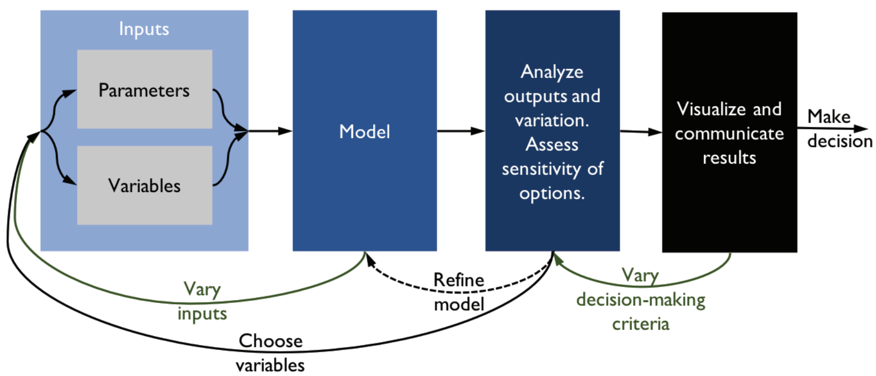
- explore a wide range of possible inputs and assumptions and identify a narrower set of possibilities that matter the most to the decisionmakers
- build confidence in assumptions and inputs (e.g., identify the most likely case)
- provide insights into risks associated with COAs caused by uncertainties

[42] For decades, researcher Paul Davis has argued that sensitivity analysis is not a good way to deal with uncertainty. These issues were first discussed in 1992–1993 (Davis and Finch, 1993) and included in a wider discussion of defense planning in 1994 (Davis, 1994). The ideas contributed significantly to DoD's embrace of capabilities-based planning a few years later (Davis, 2002), but, according to Davis, the implementation was poor. Analysts changed viewgraph titles but not their practices, and they remained wedded to big, opaque campaign models with standard scenarios. A review of these matters (Davis, 2014) is recommended reading. An appendix to that report discusses the often-misunderstood relationships between threat-based planning and capabilities-based planning.

- identify alternatives or COAs that are robust to uncertainties or variations in inputs.

Sensitivity analysis refers to any method that assesses how a system or model's output varies (and how strongly) because of perturbations in any of the variables that determine the output. Figure B.1 shows a schematic of a process for carrying out sensitivity analysis. The overarching theme is to vary inputs into a system model or decisionmaking framework and then determine how strongly the resulting outputs vary. These variables may be design variables—inputs to system performance chosen as part of the design process—or external variables representing threats and external perturbations to the system. They may also be metrics that drive decisionmaking processes, such as performance score weights. Here, we use the term *parameter* to refer to system inputs that cannot be varied by choice (in contrast to system variables).

Figure B.1. Schematic of Process for Carrying Out Sensitivity Analysis



The practical implementation of sensitivity analysis can take many forms. These methods include qualitative and quantitative methods, and methods that are deterministic and probabilistic. The general idea is the same, however. For whatever framework, inputs are varied for some baseline value and the subsequent impact on the outputs is assessed. This assessment can be done by varying *one input at a time*, or by varying many of them simultaneously. Furthermore, the inputs can be varied in a deterministic way or in a probabilistic way. With increased computing power, the availability of robust and flexible software packages and modeling frameworks, and the development of powerful analytical techniques, it is becoming increasingly possible to carry out both quantitative and qualitative sensitivity analysis in the same environment.

Sensitivity Analysis Methods and Practices

Just as there is no single method for assessing SMA, there is no single method for carrying out sensitivity analysis, although the overall framework and objectives are described above. Table B.1 lists several sensitivity analysis methods that could be employed in SMA assessments.

The scope and methods would depend on the decision context and the scope of the SMA assessment. In this section, we discuss each method in turn.

Table B.1. Candidate Sensitivity Analysis Methods for SMA Assessments

Sensitivity Analysis Method	Suitable Application
Probabilistic sensitivity analysis	Exploration of a large number of possibilities in a time-dependent fashion
Monte Carlo analysis	Determination of scenarios that are likely and scenarios that are sensitive to input variations
Influence diagram	Investigation of a wide range of scenarios in an exploratory fashion
Isoperformance analysis	Identification of ranges of inputs that yield similar outcomes.
Model order reduction	Identification of the most sensitive components of the model

Deterministic vs. Probabilistic Sensitivity Analyses

Sensitivity analysis can be carried out deterministically, probabilistically, or using some mixture of both approaches. Important factors that are used include the level of certainty underlying the system composition or its corresponding model. For decisions made against complex, dynamic backdrops and over sufficiently long timescales, often a large number of possibilities must be explored in a time-dependent fashion, and probabilistic analysis comes into play in such a situation.

Monte Carlo Simulation

Monte Carlo analysis is a catch-all term for a type of modeling framework in which any of the variables driving the system is varied according to some kind of probabilistic rule many times, so that a probabilistic understanding of the system response can be gleaned. A large exploration of variables and model states enables the analyst to determine scenarios that are likely and scenarios that are sensitive to input variations. This determination allows the decisionmaker to gain an additional level of intuition into the likelihood of outcomes and prioritize them appropriately.

A typical procedure would be to assume (either based on assumption or prior data) a certain system component characteristic x has a likelihood of occurring $P(x)$, with an associated cumulative distribution function CDF(x) (Figure B.2). Then for one run of the Monte Carlo procedure, a random number u between 0 and 1 is picked; from that, the corresponding x value, $\text{CDF}^{-1}(u)$, is determined and used as the input into the system model, from which the overall system output is tracked. This process is done over many iterations, so that a range of potential systems or worlds is realized. Monte Carlo is especially useful in systems with many components and uncertainty because it allows a large number of system inputs to be sampled in a probabilistically representative way while not resorting to brute-force inputs sweeps. Where appropriate, a priori knowledge of a variable input's probability distribution can be used; otherwise, a probability $P(x)$ is a constant or uniform probability distribution function, with upper and lower bounds on x placed based on "reasonable" values.

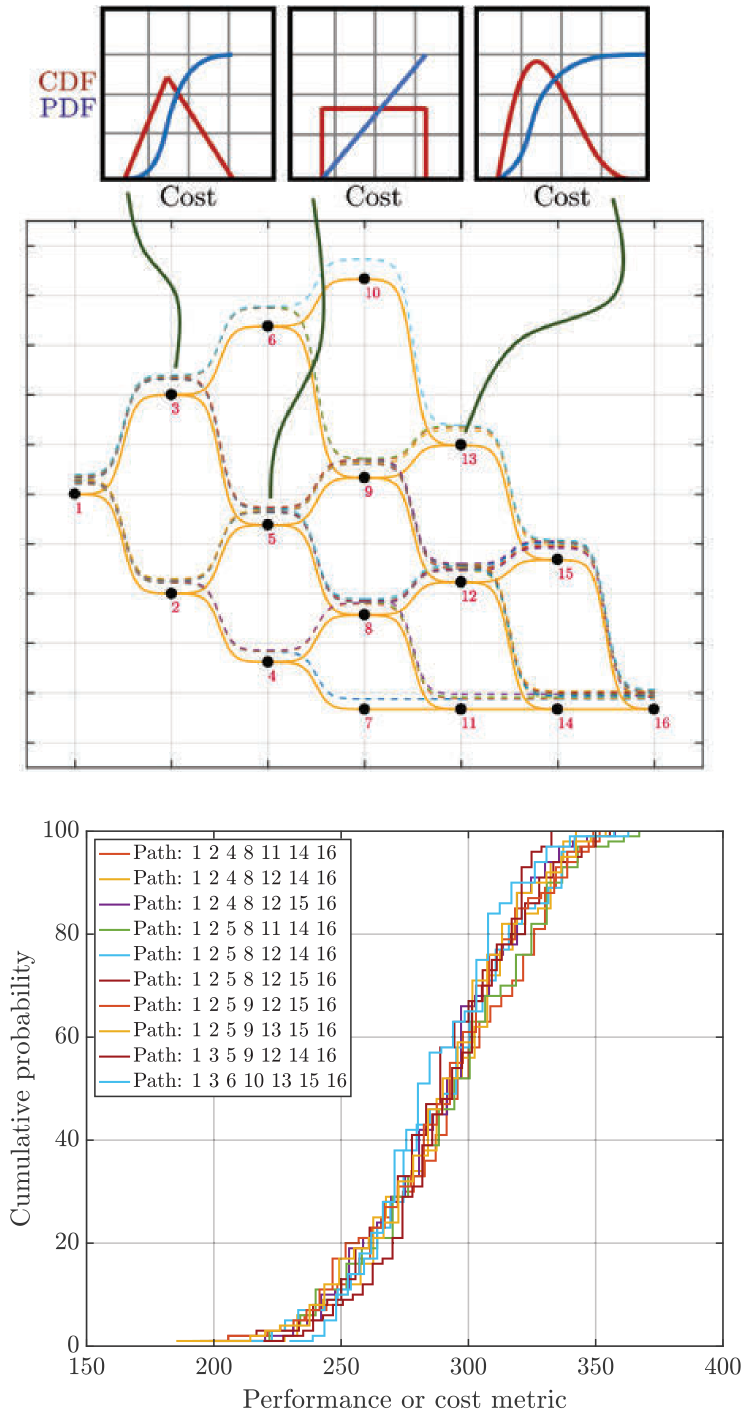
Influence Diagrams

Influence diagrams show the logical relationships between SOWs (which may have associated probabilistic characteristics) and decisions that are made based on them or lead to them (Howard and Matheson, 2005). They belong to a larger class of diagrams that more generally describe the processing and flow of information; they are related to block diagrams and Bayesian network diagrams. One benefit of influence diagrams is that they indicate relationships between decisions and world-states in easy to understand graphical terms, much like systems block diagrams (Figure B.3). *Decision trees*, which map the outcomes of one decision to another, represent a subset of influence diagrams in which only decisions are represented.

In fact, this common structure means that, while influence diagrams have traditionally focused on assigning probabilities to state nodes, the notion can be easily generalizable, and the nodes can represent systems, performance variables, or other influence diagrams. In this sense, the influence diagram can be scaled to different abstraction levels, which can be exploited for conceptual or computational practicality.

The outcomes of various decisions based on inputs can lead to the identification of "need-points," about which solutions need to be generated. Indeed, the value of influence diagrams is that they can investigate wide ranges of scenarios in an exploratory fashion. Assigning probabilities to state nodes allows us to quantify uncertainty and acknowledge that even low-probability events can have significant outcomes.

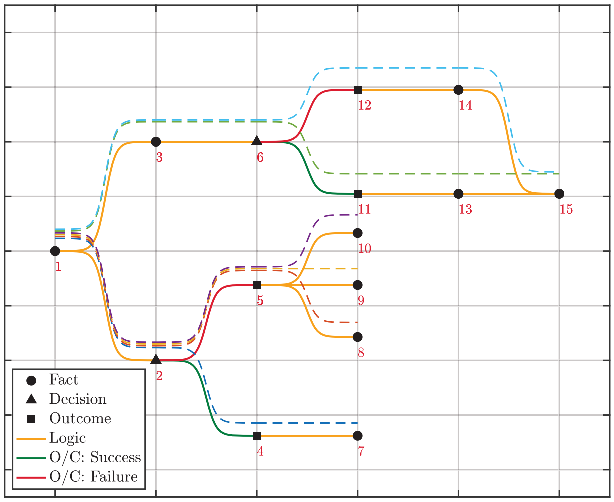
Figure B.2. Demonstration of Monte Carlo Analysis to Assess System Performance



SOURCE: RAND research based on Howard and Matheson, 2005.
NOTE: The top graphic represents a network of arbitrary context, in which information flows from node 1 to 16. We have assigned arbitrary performance scores (or costs) to each, with Probability Distributions Functions (PDFs) and associated Cumulative Distribution Functions (CDFs) for the likelihood of attaining those scores to each node; those PDFs can take whatever form, though we show for reference on the left a triangular, uniform, and Rayleigh distribution. For each possible path through the system, take the overall system performance to be a sum of the

individual scores of the nodes, although the actual overall performance or cost metric naturally depends on the system at hand. We run 50 iterations for each path, in which we sample from the PDFs assigned to each node. The bottom graph shows the resulting distribution function for the overall system performance when taken through several of the possible paths.

Figure B.3. Example Influence Diagram of Potential Logical Paths Realized as a Result of Facts and Decisions Made upon Them



SOURCE: RAND research based on Howard and Matheson, 2005.

RDM

RDM is discussed in Appendix A. RDM encapsulates many of the precepts of sensitivity analysis we discuss here. In particular, RDM employs probabilistic explorations of world-state evolutions. The analysis then identifies those results or model output (world realizations) that appear most and least often, and the ranges of the system inputs that lead to particular decision outcomes. By design, RDM carries out sensitivity analysis and, as demonstrated elsewhere in this report, provides a quantitative method for making decisions based on complex and evolving system dynamics.[43]

Isoperformance Analysis

Isoperformance analysis is concerned with identifying the sets of system inputs that yield identical or similar system performance (de Weck and Jones, 2006). In this regard, isoperformance analysis is similar to RDM, because its focus is on outcomes and the *particular* inputs that enable sets of outcomes. With these methods, the decisionmaker can focus on those choices that lead to sets of *outcomes*, rather than focusing on the variations on the inputs, the sensitivity of which may often lead to irrelevant outcomes.

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[43] The RAND-developed Rhodium Python library carries out RDM and creates visualizations of interest to decisionmakers (Hadka, 2015).

Model Order Reduction

Model order reduction is a mathematical procedure, originally developed in the context of control theory, in which a model is simplified in order to reduce its computational complexity such that only the most influential components are included while maintaining the model's "accuracy" to within a specified value (Moore, 1981). A natural outcome of the procedure is an ordering of the most influential components of one's model, such that the most sensitive components of the system's model are identified.

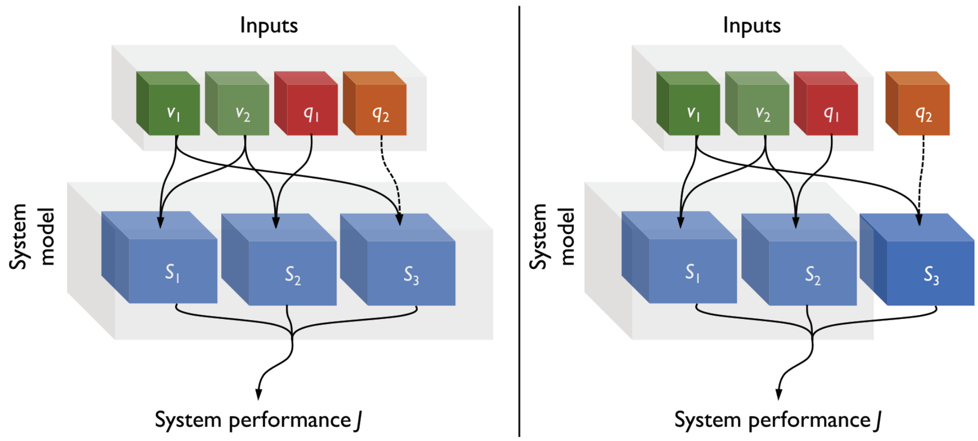
Use of Block Diagrams and Model-Based Systems Engineering

Model-based systems engineering (MBSE) is a philosophy and framework endorsed by the International Council on Systems Engineering that can be used to frame the traditional objectives of systems engineering (including high-level systems functionality and requirements generation and tracking) with a framework focused on system functionality and the models that represent them (Estefan, 2007). System models are represented as blocks (as in control engineering), and links between them encode physical and logical relationships. These linkages between system (and hence model) components are used to inform requirements flow-down. Although much of the current application of MBSE is geared toward requirements verification and traceability, from an analytical or practical perspective, MBSE readily provides a basis for incorporating various methods of sensitivity analysis—whether it be "one factor at a time" or a factorial Monte Carlo experiment—into a physics-based framework.

Accounting for "Unknown Unknowns" in Sensitivity Analysis

Inputs with deep uncertainty, or "unknown unknowns," present a challenge in carrying out sensitivity analysis. We describe one potential way of accounting for such uncertainty. For instance, if we wish to assess the impact of losing a particular sensor during a space fight, we may wish to consider the effect of kinetic impactors, directed energy weapons, or space weather events on that sensor's capabilities. We can model all the possibilities (various attacks and natural events), or we can isolate the subsystem of which the sensor is a part and vary *its* overall performance characteristics in order to assess the resulting impact on the overall system. For example, proceeding in this way eliminates the need to know what is causing the variation in performance of the sensor but enables the analyst to assess its subsystem's impact on the overall system (Figure B.4).

Figure B.4: Accounting for "Unknown Unknowns" in Sensitivity Analysis



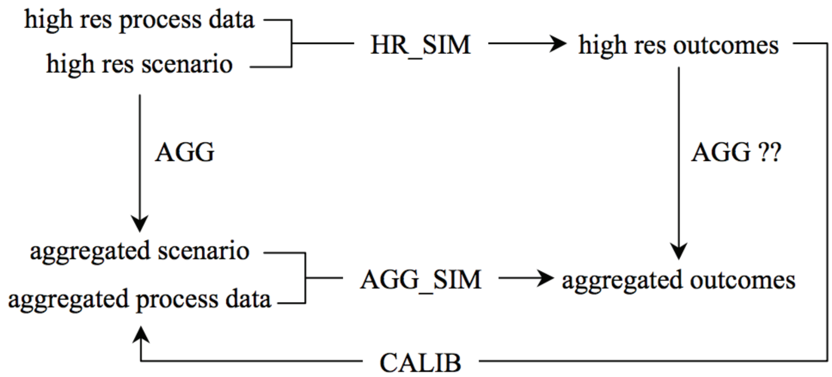
NOTE: On the left, we show design variables v_1 and v_2, parameter q_1, and an unknown unknown q_2 as inputs to a system model comprising subsystems S_1, S_2, and S_3, which together yield a performance index J. We might assess the sensitivity of the system to its inputs. But because the nature of q_2 is supposed here to be unknown completely, in assessing the system performance sensitivity to its inputs, we must isolate the subsystem it might act on (S_3) and vary its performance as part of the analysis (shown on the right).

Accounting for Aggregation of Models in Sensitivity Analysis

When we have a simple closed-form model, or a discrete event model that has well-understood dependencies and has reasonable run times, running a sensitivity analysis with one of the well-established techniques is fairly straightforward. But with combat modeling, in which we attempt to understand the operational effectiveness of large aggregate systems of systems, this analysis becomes a challenge. As noted in our interviews and in the literature, no single model can represent all aspects of space (Olsen, 2002). Also, if one is to look at operational effectiveness on a campaign level, one would have to integrate lower-level, higher-fidelity engineering, engagement, and mission-level model results to inform the top-level campaign models through a complex process of going from very detailed scenarios and aggregating for the next level of abstraction in order to get the results from each level of fidelity and then continuing to aggregate the results to inform the final campaign-level model, as shown in Figure B.5 (Caldwell et al., 2000).

In this work, Caldwell et al. looked at a specific set of analytical models and discrete event simulations and presented a method for aggregating the results and for using the high-fidelity model to calibrate the aggregate simulation (Figure B.5). The high-fidelity models are run against the simplified aggregate scenario to verify that the results are consistent.

Figure B.5. Aggregating Scenarios from Higher Resolution to Lower Resolution



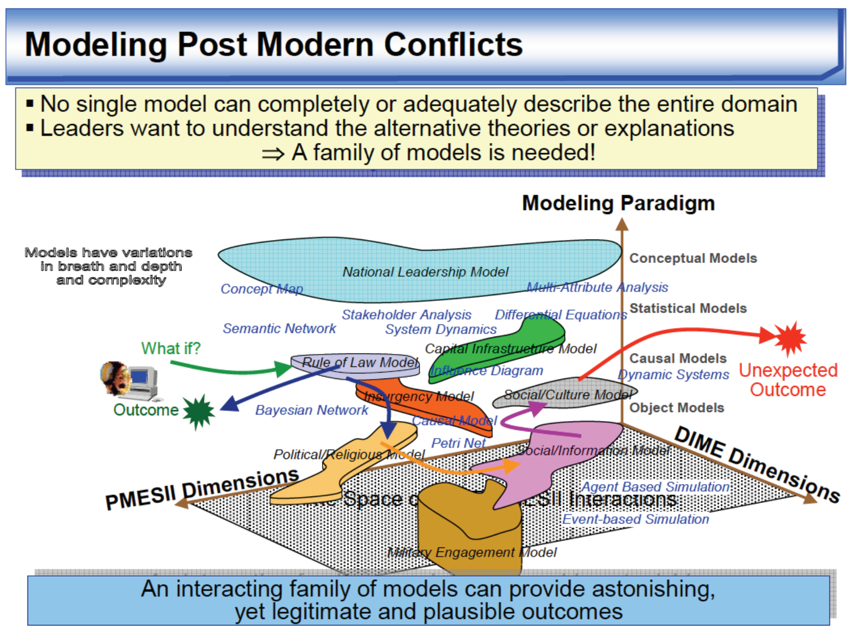
SOURCE: Caldwell, 2000, p. 1-10.
NOTES: HR = high resolution; SIM = simulation; AGG = aggregation; CALIB = calibration.

In all cases, the analyst will have to decide how to do the aggregation and how to calibrate the aggregate models. The process of using multiple models and aggregating several levels to get to the campaign model makes it difficult to perform a full sensitivity analysis, because the time and effort it would take to run all levels and conduct a sensitivity analysis comprehensively would be intractable. In practice, a detailed sensitivity analysis is run at the higher-fidelity models before aggregating to understand the range of outputs based on the assumptions. Care has to be expended to ensure that all assumptions and scenario inputs are consistent across all models and aggregation levels and that their impact on each modeling layer is understood as much as possible. Then extra care will have to be taken to understand how the aggregation might create artificial sensitivity to some of the inputs. It has been observed in past studies that slight changes in inputs can create large effects in the output of the model that cannot be rationalized and can be an artifact of the aggregation process.[44] One must make sure to spend time to understand where these potential sensitivities are and account for them either in the aggregation or in designing sufficient sensitivity runs for some key inputs in the aggregate model. This sensitivity analysis should be performed at each aggregation level before going to the net to ensure we identify and mitigate any of these artificial aggregation effects.

[44] Two examples of this effect: In a past study, we modeled different SATCOM architectures and tried to estimate kill ratios for a brigade-level force. Two communications architectures that should have provided the same level of messaging support showed dramatically different kill ratios. While never really resolved, it seemed that the way the communications effects were aggregated created an artificial jump in the results. For example, if radio propagation was blocked by tree heights of 10 meters but can make it through trees at 9.9 meters, and we modeled everything using a uniform 10-meter-tall forest, this will create an all-or-nothing result. In real life, things are more gradual and nuanced. In another case, we modeled the system to drop a percentage of messages, and in one run it happened to drop the initial message ordering a force to deploy. The model did not account for the fact that the message would have been resent. The artificialities in the aggregation of the lower-level effects can create unpredictable and false results.

In the case of SMA assessments, this analysis may be particularly difficult, in that many different space effects, models, and levels of aggregation would have to be taken into account. There are some examples of work trying to resolve this issue. For instance, in the DARPA Conflict Modeling, Planning and Outcomes Experimentation (COMPOEX) program, analysts had a very complex modeling problem at the campaign level that included multiple models at very different levels and effects that covered a wide range beyond simply the military effects, as shown in Figure B.6 (Kott and Corpac, 2007).

Figure B.6. DARPA COMPOEX Modeling Two Dimensions of Political, Military, Economic, Social, Information, Infrastructure (PMESII) Effects and Possible Diplomatic, Information, Military, and Economic (DIME) Actions



SOURCE: Kott and Corpac, 2007.

This complexity seems to be more relevant to the space modeling problem, in which political, economic, and even international law come into play and will affect outcomes in complex ways. The COMPOEX program developed an "option exploration tool" that defined the relationships between many inputs, like many of these models, in a way that allows one to vary inputs easily to see how sensitive the outcomes might be to different inputs. Whether a tool like COMPOEX could be built for conflict in space is unclear but worth further investigation. There is currently a DARPA program called Hallmark Software Testbed that promises to develop and integrate enterprise software architecture and create a Space Enterprise Analysis Capability (Peck, 2017). If this Space Enterprise Analysis Capability is sensitive enough to many different types of inputs and assumptions and can run test cases and what-if scenarios in a reasonable amount of time, it could make any sensitivity analysis much easier to perform.

Visualizing Sensitivity Analyses

An important aspect of carrying out sensitivity analysis is the visualization of the results. As part of the analysis, relationships will be established that link the variations in the system inputs to outputs or outcomes. While data tables are useful, it is difficult for decisionmakers to intuit patterns by simply looking at numbers, so it is essential that sensitivity analysis results are presented in an unambiguous way that makes relationships between the different variables clear.

One major challenge—which is becoming more widespread because of the increase of computational power and hence the ability to carry out broader exploratory analysis—is being able to visualize a large number of inputs at once. Visualizing a system performance index or decision metric that is a function of N parameters (including, possibly, time) requires a means of visualizing at most $N+1$ variables; in the case of multicriteria decisionmaking, where M criteria are used, $N+M$ dimensions are required. The limitations imposed by our spatial and temporal reasoning capabilities can be mitigated in two ways:

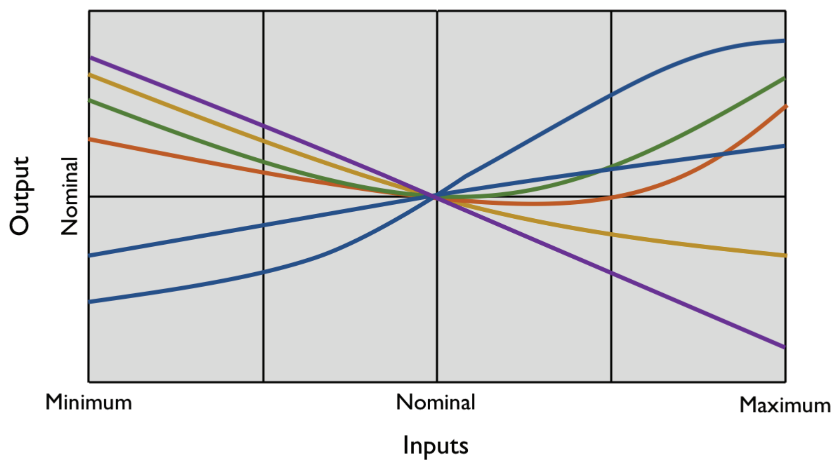
- *Data reduction*: As part of the sensitivity analysis, the most functionally important subsets of the system or decision model variables will be identified.
- *Added dimensionality to the visualization*: Data need not be limited to points and lines in two- or three-dimensional plots. Marker sizes, line widths, colors, shading, and transparencies can be used to add additional dimensionality to the data presentation.

Together, these methods can be used to present data to decisionmakers to highlight outcomes of sensitivity analysis in a maximally effective and informative way. Next, we highlight methods that are commonly used in presenting sensitivity analysis outcomes. We believe that the recommended sensitivity analysis methods and practices discussed earlier can be augmented with these techniques, to the benefit of decisionmakers.

Spider Diagram

A spider diagram is similar to a traditional line graph indicating variations in model output as a function of corresponding variations in input variables (Figure B.7). The y-axis represents the performance index, while the x-axis represents all the variables under consideration, scaled such that the smallest and largest values on the axis coincide with the minimum and maximum values of the inputs explored, respectively; the midpoint of the axis represents the baseline value of the variables. Output values are plotted separately for all variables, so that all lines intersect in the middle of the diagram. The lines splay outwards, similar to a spiderweb, and the outermost lines represent those to which the system is most sensitive. As with any visualization technique that places multiple variables on the same axes, care must be taken that the viewer is aware of the differing scales for each variable. Such a graph can also be misleading if the variations in some inputs span multiple orders of magnitude, for instance, while others span a relatively small range.

Figure B.7. Spider Diagram



NOTE: Inputs are varied around their nominal values and from their minimum and maximum ranges. They are plotted on the same axes, with each individual axis scaled accordingly. In the example here, each colored line corresponds to the output given by varying a single input.

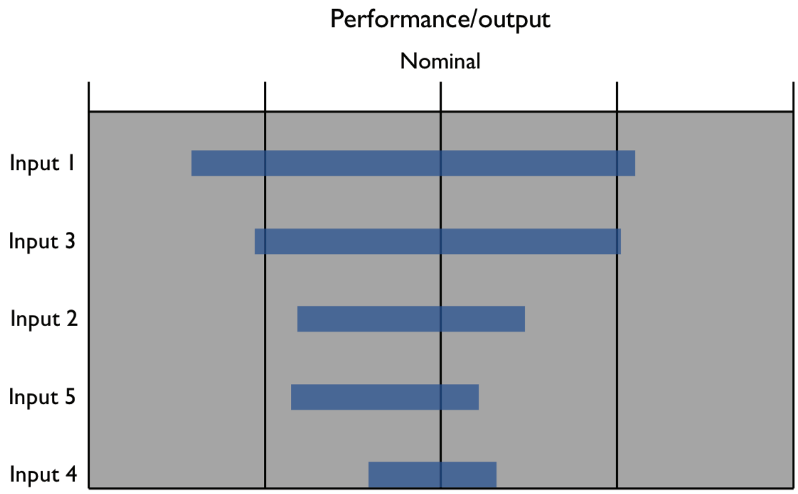
Tornado Diagrams

A tornado diagram is a means of visualizing a sensitivity analysis carried out using the "one variable at a time" method. That is, it shows the variation in the model output caused by varying one input variable at a time. Each input is varied over a range, and for each variable, the upper and lower bounds in the overall model output (relative to a baseline case) are shown (Figure B.8). The name derives from the fact that the variations are depicted by horizontal bars and the ranges are shown in order (from top to bottom) of decreasing variation, thus indicating the hierarchy of those variables that (when varied independently from all other variables) lead to greatest variation in the model output.

Waterfall Diagrams

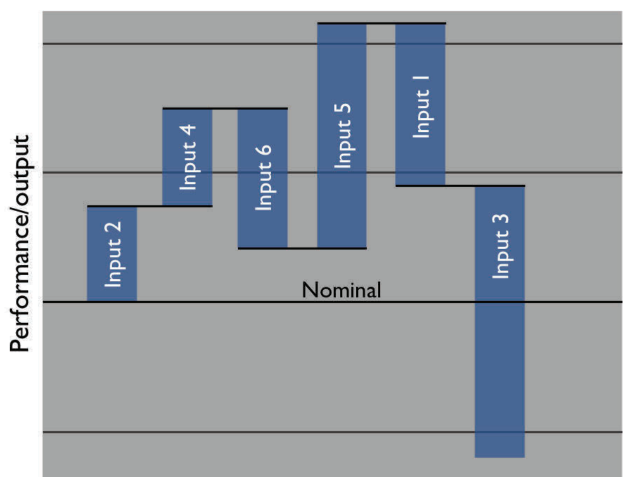
A waterfall diagram visualizes the same of type of information shown in a tornado diagram, although arranged somewhat differently. A waterfall diagram is intended to show how the baseline model output changes as different variables "fall" from the base case to a low case or rise from the base case to a high case (Figure B.9). A challenge with waterfall diagrams, however, is arranging the variables in a logically meaningful way. If variations in inputs are represented sequentially, intuition leads one to surmise that there is a syllogistic relationship between these variables, even when that is not the case. In this regard, care must be taken when using waterfall charts.

Figure B.8. Notional Tornado Diagram



SOURCE: RAND research based on Parnell et al., 2013.
NOTE: The inputs on the left are ordered based on sensitivity of output to input variation.

Figure B.9. Example Waterfall Diagram



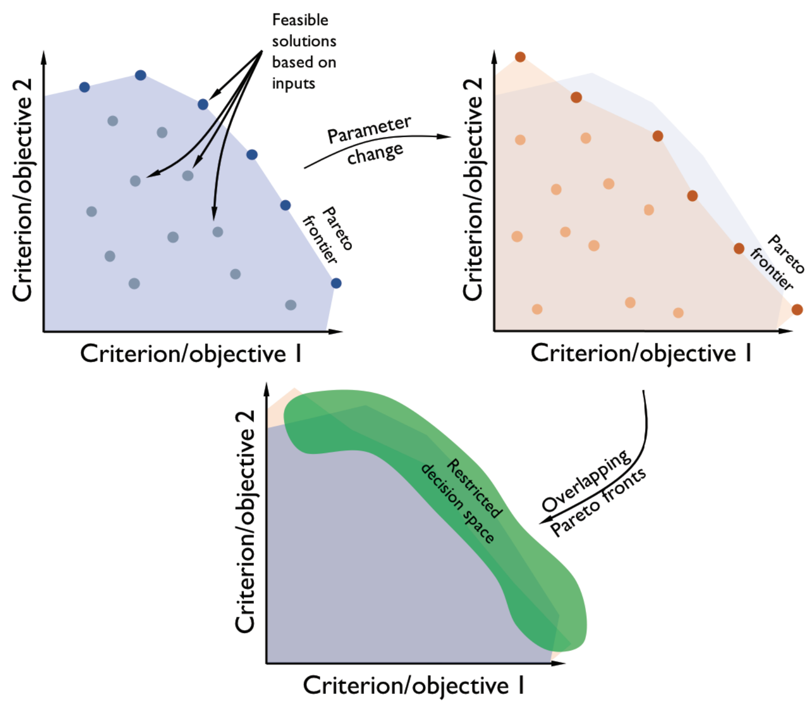
SOURCE: RAND research based on Parnell et al., 2013.
NOTE: The inputs' effect on overall output may be ordered sequentially or temporally, or based on overall sensitivity, but in practice this ordering must be chosen carefully.

Pareto Frontiers

In multicriteria decisionmaking (or multiobjective optimization), in which designers, analysts, or decisionmakers rely on several different criteria to inform their decisions, it is usually not possible to identify a solution (i.e., a set of input variables) that enables all the criteria to be simultaneously optimal. Hence, designers or decisionmakers explore all the sets of possible criteria that can be realized and find those criteria (or objective functions) whose value cannot be increased without decreasing that of the others. The set of all criteria that satisfy this constraint is referred to as a Pareto optimal set, or Pareto frontier. These sets enable decisionmakers to significantly constrain the decision space and focus on just those input variables that enable potentially optimal choices. Pareto frontiers can illuminate several aspects in the context of sensitivity analysis, as shown in Figure B.10.

Traditionally, Pareto diagrams are presented in two-dimensional slices of a larger *N*-dimensional set of criteria. With increased visualization capabilities, three-dimensional, interactive visualizations (whose dimensionality may be augmented in various ways) can enable decisionmakers to intuit the decision space more broadly.

Figure B.10. Pareto Frontier for Multicriteria Decisionmaking

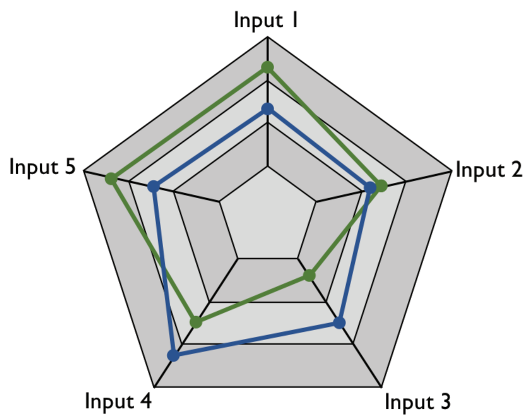


SOURCE: RAND research based on Brown and Eremenko, 2009.
NOTE: On the top left, the values of sets of criteria (or objective functions) are plotted (grey circles). Each is a function of decision or system inputs. The collection of points comprising the frontier (blue circles) are those criteria or objectives whose values cannot be increased without degrading those of the other criteria. This collection is known as a Pareto frontier, and can be used by decisionmakers to significantly constrain the decision space for further trade-off investigation. Varying parameters enables decisionmakers to investigate how the Pareto frontier changes because of these parameter variations (top right panel) and identify a space of Pareto frontiers upon which decisions or designs can be identified. Similar techniques have been suggested for space acquisitions (Brown and Eremenko, 2009).

Radar Diagrams

Radar diagrams show ranges of variables arranged in a circular fashion. Each “spoke” represents a different variable and its particular ranges (Figure B.11). Radar diagrams are especially useful in the context of isoperformance analysis, as it focuses on simultaneous visualization of the ranges of the input values themselves that yield identical overall outputs (Smith, 2014).

Figure B.11. Example Radar Diagram



SOURCE: RAND research based on Smith, 2014.
NOTE: Inputs are arranged radially and show values for a given output. Scales on each "spoke" vary based on each input. Sets of input values are shown for two different outputs, corresponding to the green and blue lines.

Summary

Conducting sensitivity analysis is a common practice in decision support analysis to characterize the impact of uncertainties on the outcome of the analysis (e.g., cost assessments, technical performance assessments, operational effectiveness, etc.). While uncertainty in input data and the need to make assumptions in SMA assessments are not unique to space, we observe that the uncertainty may be greater in the space domain because of relative newness of space warfighting concepts. Thus, SMA assessments may need additional sensitivity analysis to overcome the challenges associated with the lack of established baseline and uncertainty bounds for inputs and assumptions. The sensitivity analysis methods and practices discussed in this appendix should help enhance SMA assessments and better support decisionmaker needs.

Appendix C. Example Application of Campaign Outcome–Guided Mission-Level Analysis to an SMA Assessment

Motivation

This appendix describes an analytic method that can help to link SMA assessments to operations in other domains, and to enable assessments of SMA spanning multiple space mission areas. Chapter 4 identified shortfalls in these types of SMA assessments.

We call the approach *campaign outcome–guided mission-level analysis*, and the approach is commonly used by air component force planners. For instance, this approach is used to provide decision support for acquisition decisions on aircraft and weapons. In these trades, a suite of sensors, platforms, and weapons is modeled in the context of a scenario in which CONOPS, environmental factors, and adversary actions are represented. Key measures of performance and effectiveness are collected, compared, and analyzed in a fight to see which systems meet the warfighting goals. Companion analysis on the cost of these systems makes up a cost-effectiveness analysis.

Campaign- and Mission-Level Analysis

Campaign models, while weaker on details than higher-fidelity models, provide trade-off analysis in the context of war outcomes. A traditional force structure example might be two proposed mixes of the numbers of fighters and bombers. A focused analysis on supporting enablers, such as space, can similarly feed input into a campaign model. For example, analysis on space-based ISR or SATCOM can provide measures of performance that are represented in a campaign model. Analysts could explore alternative space-based ISR architectures that support a fixed fighter and bomber force. In this way, campaign models allow enterprise-level trades that are tied to campaign outcomes.

Mission models provide effectiveness trades for system capabilities and CONOPS. Direct linkage between system changes and mission outcomes is clearer than in campaign models. However, mission models do not capture enterprise-level trades, nor do they tie capabilities to campaign outcomes (because they are not modeled). Further, they do not consider effects on other theaters.

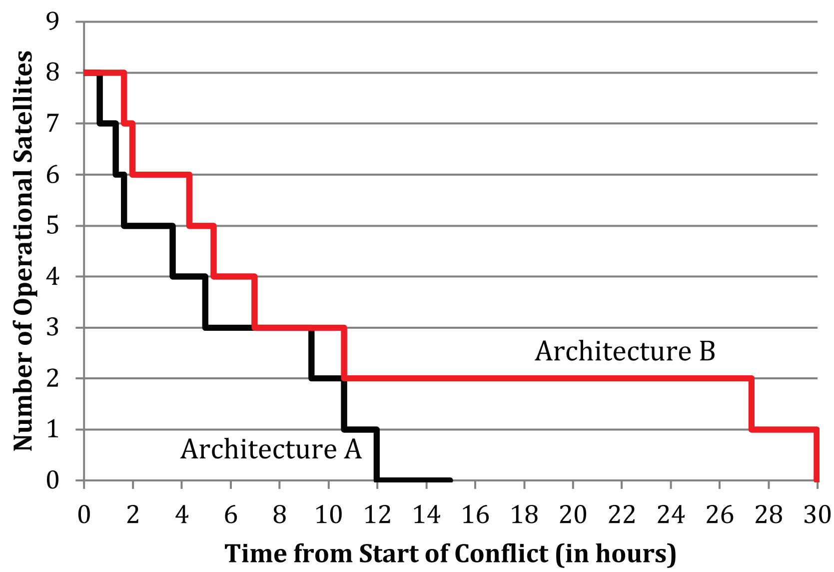
Example Assessment: Degrading Adversary's Long-Range Strike Capability

Consider a major campaign in which an adversary employs 12 long-range bombers from a given base to achieve its military objective, and in which campaign analysis shows that to meet

Blue military objectives of halting the attack, the initial attack needs to destroy six of the Red bombers within 12 hours from the start of the conflict and the remaining six in the following 12 hours. Observe that this approach uses a campaign-level objective (i.e., halt the attack) to set a mission-level objective (i.e., destroy a percentage of Red bombers in a given amount of time).

Let us assume that the decisionmaker needs to understand investment choices between SMA of the space-based ISR capabilities providing targeting support for air-launched weapons and the number of weapons required in the inventory to destroy the Red bombers. Red may attack the space-based ISR using counterspace weapons. We employed a MATLAB model to assess the tactical drawdown curve associated with the two alternative space architectures subject to counterspace attack, using notional data. For instance, the two space architectures may draw down at different rates because they employ different defensive measures. Figure C.1 shows the drawdown curves we used in our assessment. The figure shows that architecture B draws down more slowly than architecture A, and hence architecture B has enhanced SMA as compared with architecture A in the context of the counterspace attack.

Figure C.1. Drawdown Comparison for Space Architectures A and B



Next, we consider the contribution that space-based ISR provides to the terrestrial fight. At one extreme, if space-based ISR provided Blue with perfect understanding of where the Red bombers were located, Blue would employ a unitary weapon at each parked aircraft. At the other extreme, in which Blue does not have a current accurate picture of bombers on a given base, Blue may need to employ a unitary warhead on all possible parking areas, taxiways, and runways. The region between these two extremes is where the analysis occurs. We assumed that the adversary employs camouflage, concealment, and deception techniques, including the use of decoys. We assume a notional Red air base with a capacity of 50 possible locations for bombers in which 12 bombers are stationed along with 12 decoys, i.e., 26 locations are vacant. The analysis compares two space architectures that could provide ISR support to the mission, and those architectures are subject to counterspace attacks. We further assume for simplicity that a constellation of two satellites is sufficient to provide the minimum essential data needed to support the terrestrial mission. The decisionmaker needs to consider the trade-off in the number of weapons needed to meet the operational objective versus the SMA of the two space architectures.

We used a variety of models to assess the kill chain for this notional example, including the JMEM, to calculate the weapon's ability to destroy the target based on key parameters, such as weapon type and size, blast and fragmentation pattern, and target location error. We characterized the spaced-based ISR capability to distinguish bombers on bases from decoys in terms of the K-factor, which represents the discrimination capability of the satellite's sensor and which we assume is equal for both architectures. We present a simple trade in which the number of weapons needed to meet the commander's goals is calculated as a function of the K-factor. The analysis also considers the weapon's effectiveness. The number of weapons W (missiles) required is based on the total number of objects that need to be targeted and is given by

$$W = \frac{ln(1 - P_{eff})}{ln(1 - P_{kss})} \times T$$

where P_{eff} is the required weapon system effectiveness, P_{kss} is the PK of an individual missile (that is, a single shot), and T is the total number of target objects. The number of decoys mistaken for a target is $D \times P_{fa}$, where D is the number of decoys and P_{fa} is the probability of false alarm, i.e., the probability that you identify a decoy as a real target and that is dependent on the K-factor and acceptable leakage probability.

Figure C.2 illustrates the effect of the space contribution, through the K-factor, on the number of missiles needed to meet the commander's goals of initially destroying six of the 12 bombers. Two weapon PK values are provided. The results illustrated in the figure indicate that the knee in the curve occurs at a K-factor value of two for both missile capabilities, and, at this value, the number of weapons needed is about half what would be needed if no discrimination capability existed, i.e., Blue would target 12 objects and assume that six are bombers. The contribution from the space domain assumes the satellites are available and have sufficient access to the Red base, i.e., weather and revisit rate are sufficient to see the bombers at the base. We used the same approach to assess the number of weapons needed for the follow-on attack.

Figure C.2. Number of Weapons Needed to Destroy Six Bombers Within First 12 Hours

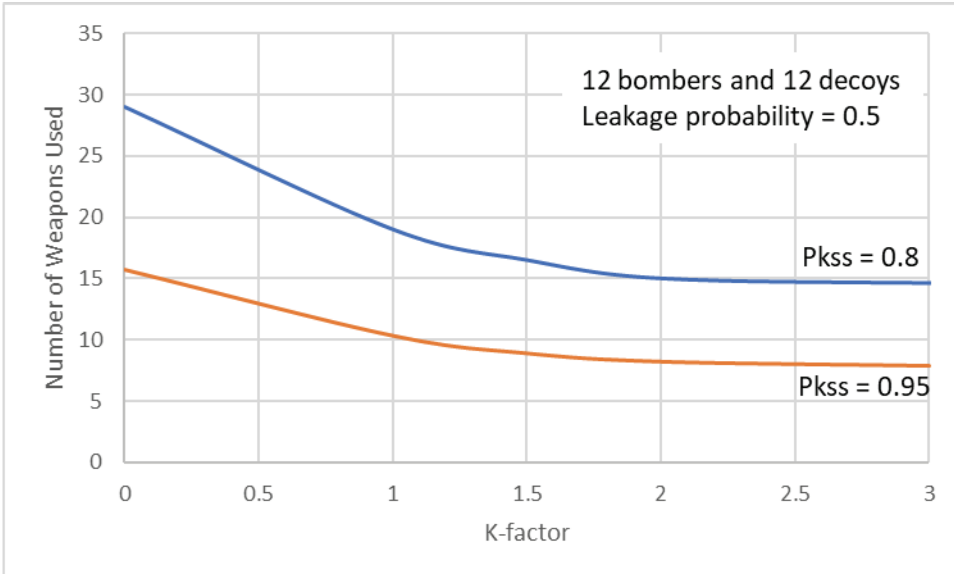


Table C.1 summarizes the results of the analysis. Each row corresponds to a different value for the K-factor, which parameterizes the capability of the space architectures to discriminate bombers from decoys (the two architectures are assumed to have identical discrimination capability). We see that the difference in SMA for the two space architectures affects the number of weapons needed. The columns provide the number of weapons needed to accomplish the initial attack, follow-on attack, and the total for both attacks. We see from the results that more weapons are needed for space architecture A than B, which is due to the enhanced SMA associated with architecture B.

Table C.1. (Notional) Trade-off in Weapons Needed to Meet Operational Objective Versus Space Architecture

K-Factor	Initial Attack (Within 12 Hours)		Follow-On Attack (12 to 24 Hours)		Total Number of Weapons	
	Architecture A	Architecture B	Architecture A	Architecture B	Architecture A	Architecture B
0	29/16	29/16	92/50	29/16	121/67	58/32
1	19/10	19/10	102/55	32/17	121/65	51/27
2	15/8	15/8	106/57	33/18	121/65	48/26
3	15/8	15/8	107/57	22/12	122/65	37/20

NOTE: Results given for Pkss confidence interval of 0.8/0.95.

Observe that the results of the campaign outcome–guided mission-level analysis directly links an SMA assessment (the drawdown rates of two space architectures subject to counterspace attack) to operations in another domain (the number of air-launched munitions needed to halt an attack). Although our example assessment illustrated how to conduct an assessment spanning a space and air mission, the same approach could be used to conduct an assessment spanning two space missions.

Appendix D. A Perspective on Explicit and Tacit Boundaries for Information-Sharing and Examples

This appendix describes explicit boundaries for information-sharing, which follow from formal classification and need-to-know qualification, as well as tacit boundaries for information-sharing, which arise informally. This appendix also describes two examples in which different organizations developed agreements and approaches that facilitated communication of information across tacit boundaries while protecting sensitive details and organizational equities. We draw insights from these two examples. Some of what follows is based on the personal experience and perspective of a coauthor.

Explicit and Tacit Boundaries for Information-Sharing

A sensitive mission capability lives within explicit and tacit boundaries. Explicit boundaries follow from formal classification and the need-to-know qualification, which by design restrict information access and an ability to share information about the program. These boundaries also guide how computing, network, storage, and communication and display systems and networks use sensitive information. These restrictions are well considered, deliberate and, in the most sensitive cases, require approval from extremely high authority to grant access to program information. Restrictions will also apply to an activity itself, such as test, training, mission rehearsal, or a knowledge of operations tasking or execution.

Tacit boundaries arise informally from the actual work practice, required education or training, or from factors associated with a selected approach to the work.[45] Sometimes we talk about these boundaries as a community's culture or attitude, which is its approach to work. They shape the process, the understanding and accepting of risk, or may be related to attributes in the operational environment. The tacit boundaries arise slowly, as they are the consequence of practice and not explicit direction within the community of practice. If the mission activity is separated from conventional operations, it may be on a different evolutionary path or, in the case of special forces operations, assume a higher level of experience and maturity during execution than conventional forces.

Explicit boundaries and the processes they influence set formal thresholds that must be reached before access is granted or information is shared. However, tacit boundaries may not be visible even within the community until studied in an objective sense. We are all familiar with

[45] Brown and Duguid (2000) contains an insightful discussion of tacit information and barriers we unknowingly place on sharing information. The work stresses that human socialization of information is a key component of information-sharing.

situations in which language and professional terminology evolve within a community to a point where people without the specialized training or education need time to assimilate when periodically attached to a community for work. Even then, those outside the community will rely on translators or other guides. Tacit boundaries may also arise when a sensitive mission or program capability develops in isolation. When explicit guidance, such as a classification guide, is not periodically reviewed, the boundaries that guidance creates may lose their purpose and restrict information-sharing for no security or mission purpose.

Boundaries create problems for mission integration when an authority, such as a joint force combatant command commander and a joint planning staff, need to better integrate mission capabilities within a battlespace. They may cause a planning staff to undervalue, miss required dependencies, or fail to determine the true potential of a sensitive capability. Likewise, the sensitive mission community may become isolated and lose relevance within a joint force context. The community's use and ability may be truncated as commanders evolve their combat force planning and employment processes. Neither community may be fully aware of how isolation may restrict use.

A good example of an expansion of boundaries is the mission capability of the Defense Support Program (DSP) satellites. Since the early 1970s, the system supports the North American Aerospace Defense Command (NORAD) Tactical Warning and Attack Assessment system, providing a second phenomenology to radar-based systems (Northrop Grumman, 2018, and USAF, 2015). The system, developed to globally detect an intercontinental ballistic missile launch, expanded to include other missile-launch warnings through operations community socialization with other combatant commands during the Gulf War and even later in pinpointing where a C-141 exploded and was lost in the South Atlantic Ocean (Hansen, 2004). The system originally focused narrowly within a single mission but gradually expanded as the system capabilities and product's ability became better known within conventional force commanders. This expanded mission set, based on system capability, helped guide follow-on DSP development as well as operational integration. DSP mission personnel became more familiar with a broader customer base and its needs. As tacit boundaries to use opened up, the explicit boundaries were reviewed and gradually evolved with the realized capabilities.

Our intent here is to encourage and provide additional rationalization for efforts to reach across sensitive programs to better reflect inherent space capacity and potential unmet mission needs from space systems and programs. Efforts by the JSWF are useful, but the effort should also include more-deliberate information-sharing and learning venues that involve lower-level working contact between space mission entities and the broader joint operations and planning communities. With the working experience from these information-sharing venues, it should be easier to better focus campaign outcome–guided mission-level analysis linking SMA assessments to operations in other domains and joint warfighting.

We realize that any cross-mission and domain sharing must comply with explicit classification guidance and the need to know. We also know that efforts must therefore be deliberate and well considered to accomplish objectives for better-informed mission analysis, to explore further joint application, and to identify potential areas in which dependencies or operational constraints may affect delivering an effective mission capability.

What follows are some specific examples in which an isolated mission community reached a point where a deliberate effort needed to be made to learn and gain a higher vantage point. Note that in both examples, this need was recognized at the working level first, where exchange of information had atrophied an ability to work well across mission boundaries. Also, a good part of the knowledge gained was from working together toward an objective outcome.

The next section will provide the following examples:

- U.S. Navy and USAF antiship defense and attack exercise—WestPAC Readiness-82
- USAF Civil Engineer Functional Support to Sensitive Mission—Nevada Test and Training Range (NTTR) and Nevada National Security Site (NNSS).

The aim is to illustrate how information-sharing improved within an isolated operations community while helping to ensure compliance with classification and need to know. The examples help explain how a deliberate effort may help lower tacit thresholds, comply with explicit guidance, and help sensitive mission capabilities learn and adapt to external factors as necessary.

While both examples reflected concern at the operations level, the specific venues were initiated by interest or concerns of senior leadership relatively high in the organization hierarchy. The venues, however, worked directly with working-level personnel engaged in their normal operations environment. A large part of the learning took place while working together and from the documentation created from the interaction. The immediate lesson here is that senior leaders in the NSS community should undertake a deliberate effort to identify key information needs to support SMA assessments and application to the broader joint warfighting community.

Example 1: WestPAC Readiness-82

This example describes a U.S. Navy and USAF antiship defense and attack exercise called WestPAC Readiness-82. Two mission capabilities with deep knowledge and sensitive information sought a working relationship with each other to update legacy assumptions and experiment with evolving tactics and new equipment. Service politics and need-to-know classification guidance complicated the direct exchange of information. Plus, the evolving technology and emergent threat environment meant that a direct exchange probably would not have been sufficient. The unknown nature of the required missing information and application to the two mission communities required a more iterative exchange and a working exercise in which the information would receive meaning from a work and performance outcome context.

In 1981, the U.S. Navy became concerned with Union of Soviet Socialist Republics (USSR) development and probable use of advanced cruise missiles by long-range aviation forces. The speed and range of the aircraft complicated the defense of carrier battle groups, as did the standoff distance from which they could be launched. This development also meant that the potentially larger number of cruise missiles added to other attacking elements could potentially overrun the 1970s-era ship defense capability. The AS-4, or "Kitchen," cruise missile was intended for use against a U.S. carrier battle group. A capability adding a datalink enabled the aircraft to redirect the missile after launch and one version carried a nuclear warhead (Kopp, 2009).

In the pre-1986 Goldwater-Nichols Act era, the Navy-USAF service relationship showed both cooperation and the continued rivalry persisting. However, the 1970 Soviet naval growth led to increased USAF exploration of countersea roles, especially for its long-range aircraft (Swartz and Duggan, 2011, p. 73). As part of this effort, the then–Strategic Air Command (SAC) expanded the B-52 conventional missions on Guam beyond minelaying to include sea surveillance and searching for antiship munitions.

Previously, neither the Navy nor USAF spent much effort working together and, as a consequence, had very little communication or actual experience working together in these missions. When they did work together, it was generally over land attack. The Navy's concern continued with the evolving antiship defense. The USAF was experimenting with ship attack and maritime operations in general, building on work with the P-3 patrol aircraft mission and minelaying. Each group was working its program in isolation and tacit and explicit boundaries were rather high. The Navy required an unscripted partner with long-range aircraft to press ship attack and the USAF required a naval partner to gain experience with maritime operations in general and the ship attack mission specifically. Beyond the service rivalry, there were sensitivities over USAF movement into the maritime which continued to separate the two activities. Any activity needed to be away from media and other observers, at least during the early development of tactics. The central Pacific seemed a suitable area for the remoteness and the size would better accommodate the maneuvering of a large battle group. The area also was near SAC's Guam-based B-52 wing exploring maritime operations, probably the only unit which worked with Navy units on a semiregular basis. However, very little of this contact went beyond the P-3 community. There certainly was no contact with carrier-based aviation or ship defense.

Carrier aviation leadership recognized that they needed information and more experience with the potential of long-range aviation. The threat was there, but some argued for developing their own capability, such as by acquiring land-based aerial tankers and developing the Airborne Warning And Control System (AWACS). Even at the highest levels of the Navy, concern over the changing Soviet tactics prompted leadership to inquire about acquiring a maritime B-1 aircraft.

The USAF also recognized the potential for a maritime capability for its bomber aircraft, but its work on rewriting Vietnam-era conventional tactics and developing closer ties with the regional joint combatant commands was progressing slowly. USAF leadership recognized that the current B-52 was ill-equipped for antiship operations. The work with the P-3 community resulted in a major intercept (Soviet aircraft carrier Minsk) for Guam-based B-52s. They realized that to attack ships you needed to find them and fix their location before attacking. Contacts with allies (Australia and the United Kingdom) were also under way. However, the allies needed working-level experience with carrier aviation and a better window into maritime ship defense before committing to acquiring ship attack munitions, a significant fiscal outlay.

The Navy suggested using the READIEX-82 for a special three-carrier battle group exercise that would test emerging assumptions about ship defense. These assumptions included a new approach in engaging attacking aircraft called Vector Logic, carrier decoys, and a destroyer Harpoon Project. The Navy invited the USAF Guam-based B-52s to participate as an attacking force, which also included land-based Navy aggressor aircraft, electronic warfare aircraft, P-3 patrol aircraft, and a diesel submarine. The USAF agreed to model one day's attacks on Soviet tactics, but for the remainder would experiment with various tactics that included work as if equipped with the Harpoon missile (two Navy A-4 aggressor aircraft would fly in formation with the B-52s and, on a launch signal from the B-52, execute a Harpoon B missile attack profile). This was a more-rigorous attack than anticipated from the current Soviet capability.

The information-sharing challenge was to develop a structure in which the Navy and the USAF could experiment with a robust partner and work out problems with assumptions, new equipment, and emerging tactics. All while protecting sensitive capabilities. Clearly, at least for the Navy, the USAF was not at a point where it had a need to know.

Initial discussions between the key Navy (USS Midway, based in Japan) and USAF (3rd Air Division and 43rd Strategic Wing, based in Guam) units started about a year out to establish objectives from the relationship and exercise(s). Preliminary planning meetings began a year out followed with detailed planning by the exercise force commanders six months from the exercise. It became an iterative process in which each partner was given wide latitude to maneuver forces, develop tactics, and play as close to real combat as safety would allow. Analysts from CNA participated in later meetings and would station research personnel with the units under way and airborne during the exercise.[46]

The Navy aggressor force and P-3 squadron on Guam facilitated the B-52 participation but allowed the bomber planning team to come up with its own ideas for the Red air force tactical approach to finding then attacking the carriers. The Red air commander was a Navy captain with the chief tactics and planning officer a USAF officer based in Guam. Strong support from the P-3 community, the supporting A-4 naval aggressor unit, and the naval electronic warfare EB-6 unit helped with integrating bombers into the maritime operations environment.

Key to the process was a statement of objective that early on created a structure for communicating between the two groups to protect sensitive information and service unique equities. This statement acted as an informal terms of reference that allowed both groups to act with confidence and specified what needed to be shared between the two groups, while protecting the more sensitive data for both carrier defense and bomber operational details

[46] CNA is a federally funded research and development center. CNA is not an acronym.

(including sensitivities with the nuclear role and primary capabilities of the B-52 systems). It also guided the CNA observers in their placement during the exercise and data documentation.

The exercise occurred over a week in May 1982, about the same time as the United Kingdom–Argentina Falklands War in the Atlantic. In the Falklands, the Argentinian forces used the French-developed Exocet antiship missile to sink the HMS Sheffield, with the loss of 20 crew (BBC News, 2009).

In the end, both the Navy and the USAF learned a lot about what they did not know or realize about each other's capabilities and the potential for future joint operations. Vector Logic and other tools were refined. A second Navy-USAF letter of agreement for cooperative maritime operations was signed in 1983. SAC acquired the Harpoon missile, eventually equipping two B-52G squadrons (Swartz and Duggan, 2011, p.85). READIEX-82 also improved cooperation, leading to the addition of USAF aircraft to other Naval maritime exercises. The Navy did not pursue a B-1 acquisition but did experiment with a maritime modified airborne radar system on a USAF AWACS aircraft, and tanker aircraft were modified to better service naval aircraft. After the 1986 Goldwater-Nichols Act, SAC began offering B-52 maritime support for the regional unified commanders. This support included the use of B-52 antisurface warfare Harpoon and minelaying capabilities.

Example 2: Strategic Review of Range Use

In this example, civil engineering required a strategic review of range use at the NTTR and NNNS prior to land transfer renewal and sought credible assessment of sensitive activity support.

In this example, there is one primary sensitive mission capability and a USAF-level civil engineering functional supporting entity.[47] Although there were personnel in the mission vetted for the sensitive activity, their knowledge was primarily over current support and accommodation within the preset context of land use. The functional support wanted credibility when speaking to two U.S. Department of the Interior (DOI) agencies (the Bureau of Land Management (BLM) and the U.S. Fish and Wildlife Agency) on behalf of the test and training range user community, which included the sensitive mission. In addition, a U.S. Department of Energy (DOE) sensitive area bordered the range and activity overlapped the DOE installation, NNSS.

After reviewing the BLM renewal process, the USAF civil engineering function asked for the RAND Corporation's help in taking a strategic look at the NTTR in preparation for the function's formal BLM withdrawn land–renewal application. The NTTR is a multiuse USAF range and airspace complex in southern Nevada, bordered to the east and north by the DOE NNSS, which processes restricted airspace as does the NTTR. Encroachment from energy

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[47] The Deputy Assistant Secretary of the Air Force for Environment, Safety and Infrastructure was a copartner with the Air Force Installation and Mission Support Center, the current name of the center commissioning the research.

projects, increasing Las Vegas development sprawl, and competition from other eligible BLM land uses complicated the renewal application and added importance to documenting the continued need for the withdrawn land.

After the initial NTTR visit and assessment planning meetings with local range civil engineering personnel and the operations users, RAND staff proposed using use data created by a fairly new range scheduling program and relational database archive that RAND researchers helped the USAF develop in earlier work. (This program was used by sensitive mission capabilities and the NNSS activity.) These data would provide a baseline foundation to document use and then data specifying force structure changes would help propose probable use-vectors into the new BLM renewal period. Interviews and programs under development and testing would provide a means for fine-tuning the capability's likelihood of continuing or facilitate the introduction of a new capability. One insight from visits with DOI officials was that their concern was not with changing the individual actors but understanding *how* the land would be used and *consequences* for the land. A large part of the eastern NTTR was actually managed as part of a Fish and Wildlife Agency Wildlife Refuge, and much of this land was being managed to the federal wilderness standard. The BLM land also contained sensitive archeological sites, which received high marks from BLM, Fish and Wildlife, and native peoples for the USAF's protection and management practice.

What the sensitive capability programs wanted to avoid, if possible, was further opening up the sharing of sensitive information about these activities. Nevada politics, fed by development expectations for land bordering the NTTR, made land use a sensitive issue. The civil engineering community feared what it did not know and wanted to ensure any new activity fell within the renewal context. It did not want to create a breach of trust in completing the renewal process based on what could be dated legacy use.

RAND became a third party that worked with the sensitive mission capability programs, NTTR operational management, and the vetted civil engineer community in an iterative manner with review by fully vetted personnel for classification explicit guidance. In addition, the information and context flowed from the functional support community that helped sensitive missions adapt to best practices, ease possible concerns when an activity was not appropriate to land use, and plan for future activity in terms of both range capability and capacity. The third party, made up primarily of RAND researchers, created an interdisciplinary team with experience from military flying operations and training, database management and archival, federal lands management, research and development, and sensitive program management at the Central Intelligence Agency (CIA), DOE, and USAF intelligence operations and analysis.

Two reports were produced. One focused on issues related to the comanaged land by the Fish and Wildlife Refuge, USAF, and DOE, documenting the use, mitigation activity, and need to withdraw the wilderness standard of land management. The other report documented use, assessed probable future use, and recommended specific issues that needed to be addressed during the land renewal application process.[48]

Insights from the Examples

One insight suggested by the examples is that it is possible and, in many ways, preferable to create an information-sharing venue or *security construct* short of completely opening up a sensitive activity in a briefing or document reading to a larger number of people or disparate network systems. In both examples, very few people were added to sensitive information rosters and in both cases not fully vetted because of need to know.

In both examples, terms of reference for the security construct were essential for managing expectations for participants and in addressing the explicit guidance from classification guides and need to know.

In both examples, it was useful that information exchange took place within the controlled spaces of the information owner. In the first example, the Navy was very comfortable working quietly in the central Pacific and hosted the initial planning meetings in its sensitive space on the USS Midway. In the second example, the third party visited sensitive sites and met with program personnel within their space to which they controlled access. We can imagine a situation in which a sensitive capability might be willing to host an event controlled in its space rather than allow access to the data tool uses for the analysis. That situation also gives it the ability to vet outcomes with its explicit guidance prior to release.

The examples suggest that two-way exchange of information can help to update and enrich an isolated mission capability engaged in sensitive activity.

In the case of the second example, using a trusted third party made up of differing backgrounds and expertise helped to structure the information-sharing process and improve the quality of the outcomes.

While not specific to the examples, we hypothesize that classification guides require rigorous and periodic review to remain alive and useful. The role of senior leadership is to ensure that these guides receive the necessary attention—too often are reviews rarely done. A too-restrictive or out-of-date guide may create vulnerabilities for sensitive information if the underlying technology or a mission capability footprint changes over time.

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[48] These reports are not available to the general public.

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RAND PROJECT AIR FORCE

The U.S. government has taken several steps to account for the increasing likelihood that future conflicts will extend to space, including the establishment in December 2019 of the U.S. Space Force. The potential for future wars to extend to space is driving an urgent need for assessments of space mission assurance (SMA) to provide decision support. Assessments of SMA may be used as decision support for acquisition and operational decisions in the U.S. Department of Defense and intelligence community.

The research described in this report was conducted in 2018 and aims to help the national security space community enhance analytic methods for assessing SMA. The authors describe decisionmaker needs for assessments of SMA, challenges for conducting assessments, the shortfalls that may result from the challenges, and options for addressing the shortfalls.

The authors conducted semistructured interviews with decisionmakers to identify decisionmaker needs and shortfalls of assessments provided to them in the recent past. Semistructured interviews were also conducted with analysts to identify analytic methods available and to discuss challenges. Researchers examined a selection of models to better understand the capabilities of available analytic methods and their limitations. The research team also undertook its own assessments and modeling efforts to evaluate potential steps and innovations that could address SMA assessment shortfalls.

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