Defense & Security Analysis, 30(2): 106–119 (2014)

Strategy Selection: An Info-Gap Methodology

Yakov Ben-Haim*
Yitzhak Moda'i Chair in Technology and Economics
Technion—Israel Institute of Technology
Haifa 32000 Israel
yakov@technion.ac.il. Tel: +972-4-829-3262.

The evaluation and selection of military strategy requires consideration of myriad factors—social, historical, political, geographical, technological—together with vast uncertainties encompassing all these domains. Info-gap decision theory is a conceptual framework that can support these deliberations, and that has substantive implications for the formulation, evaluation and selection of strategic goals and of the means to attain them. In particular, while the analyst may desire to reliably achieve the best possible outcome, info-gap theory provides a critique of, and alternative to, the paradigm of optimizing the outcome of a decision. In selecting between strategy alternatives, the analyst must sometimes choose between one alternative that is purportedly better than another, but also more uncertain. Such a choice is a dilemma whose resolution requires the analyst to balance between the different predicted quality of each alternative, and their different vulnerabilities to uncertainty. The dilemma can be managed with the info-gap methodology of robustly satisfying critical requirements.

Keywords: strategy; uncertainty; info-gap; robustness; innovation dilemma

Introduction

War is profoundly influenced by technology, social organization, human psychology, geography and politics. Success in war requires understanding and control of these factors. War consumes vast human and material resources and demands "genius, improvisation, and energy of mind" as Winston Churchill said.[1] And yet, Clausewitz writes: "War is the realm of uncertainty; three quarters of the factors on which action in war is based are wrapped in a fog of greater or lesser uncertainty."[2] "No other human activity is so continuously or universally bound up with chance."[3]

What does this imply about successful military strategy? Exploiting surprise is only half of the story. The other half is choice of successful alternatives despite severely deficient information and understanding. How is that achieved? This paper describes a methodological response based on info-gap decision theory.

Prioritizing strategic alternatives, when facing severe uncertainty, is utterly different from prioritization based on reliable estimates of their outcomes. Under severe uncertainty, selecting an alternative must be based on a measure of confidence in achieving critical goals. Judgments of confidence must be adapted to the high-uncertainty environment of strategy selection. We will claim that estimated outcomes are not a reliable basis for strategy selection. We will argue for prioritization and selection based on robustness to uncertainty. Robustly satisfying critical requirements, as opposed to optimizing based on estimated outcomes, is a preferred methodology for formulating strategy.

We will demonstrate that many strategic decisions present the decision maker with a choice between a purportedly better option that is more uncertain than the purportedly less attractive alternative. This situation, that we will call an "innovation dilemma", is very common in decisions under uncertainty. The robust-satisfying approach gives insight into universal aspects of strategy analysis. It is also an implementable tool in specific cases.

---

*Yakov Ben-Haim is a professor in the Faculty of Mechanical Engineering, and holds the Yitzhak Moda'i Chair in Technology and Economics, at Technion—Israel Institute of Technology, Haifa, Israel. His field of research is decision making under severe uncertainty, and he developed info-gap decision theory that is applied around the world for design and planning in many disciplines.

We begin by discussing uncertainty in war, focussing on Clausewitz' concept of friction. We then introduce the idea of an innovation dilemma and illustrate it with three military-strategic examples. In the third section we formulate and illustrate the robust-satisfying methodology for evaluating strategy. A final section summarizes and concludes our discussion.

Uncertainty

Clausewitz used the terms "chance" and "uncertainty", sometimes interchangeably, to refer to two different concepts. An event occurs by chance if it is unexpected, or its origin is unknown, or its impact is surprising. Adverse chance events provoke "uncertainty, the psychological state of discomfort from confusion or lack of information".[4]

Chance and uncertainty are dangerous because they subvert plans and diminish capabilities. Warriors have been aware of both the dangers and the advantages of surprise since they first battered each other with sticks. Conventional military theorists aimed to avoid or ameliorate chance events by careful planning, military intelligence, training and discipline, communication, command and control. Clausewitz also recognized that steadfast faithfulness to mission and determination against adversity are essential in overcoming chance events and the debilitating effect of uncertainty. But "Clausewitz dismisses as worse than useless efforts to systematize warfare with rules and formulas. Such systems are falsely comforting, he says, because they reduce the imponderables of war to a few meagre certainties about minor matters".[5] Clausewitz' most original contribution was in building a systematic theory of war in which the unavoidability of chance, and its opportunities, are central.

Why is uncertainty (in the sense of lack of knowledge) unavoidable and fundamental in war? Clausewitz' answer is expressed in his metaphor of friction. As Herbig explains:[6]

> "Friction is the decremental loss of effort and intention caused by human fallibility, compounded by danger and exhaustion. Like the mechanical phenomenon of friction that reduces the efficiency of machinery with moving parts, Clausewitz' friction reduces the efficiency of the war machine. It sums up all the little things that always go wrong to keep things from being done as easily and quickly as intended. . . .
>
> "What makes friction more than a minor annoyance in war is its confounding with chance, which multiplies friction in random, unpredictable ways."

War, like history, runs on the cumulative effect of myriad micro-events. Small failures are compounded because war is a coordinated effort of countless local but inter-dependent occurrences. Generals, like symphony conductors, choose the score and set the pace, but the orchestra plays the notes. A mis-tuned violin, or a drummer who mis-counts his entry, can ruin the show.

Uncertainty frequently originates at the tactical rather than the strategic level. The general can't know countless local occurrences: a lost supply plane, failed equipment here, over-reaction there, or complacency someplace else. As an example, the New York Times reported on 27 November 2011:[7]

> "The NATO air attack that killed at least two dozen Pakistani soldiers over the weekend reflected a fundamental truth about American-Pakistani relations when it comes to securing the unruly border with Afghanistan: the tactics of war can easily undercut the broader strategy that leaders of both countries say they share.
>
> "The murky details complicated matters even more, with Pakistani officials saying the attack on two Pakistani border posts was unprovoked and Afghan officials asserting that Afghan and American commandos called in airstrikes after coming under fire from Pakistani territory."

Central control is critical, but also profoundly limited by the micro-event texture of war. Uncertainty is central because it emerges from the churning of individual events. This adds up to Clausewitz' concept of friction: global uncertainty accumulating from countless local deviations.

Strategic uncertainty also arises in a realm quite different from Clausewitz' concept of friction. A state's transformation of its mode of war is often both slow and highly uncertain. Decades may be required for strategic conceptions to develop and be assimilated into government and military hierarchies, as Tomes illustrates for the US from the Vietnam to the Iraq eras.[8] The strategic planner must deal with uncertainty in evolving doctrine and weapon systems that may be available or adopted in the future.

Innovation Dilemmas in Military Strategy

Our study of strategy and uncertainty will concentrate on a class of decision problems that we will call innovation dilemmas. We begin with several examples.

The security dilemma

Consider the following situation, discussed extensively by Jervis.[9] States develop both defensive and offensive weapons, but are sometimes unable to reliably distinguish between these categories of weapons in other states' arsenals. For example, in the inter-war period of the 20th century, Britain's naval capability was sufficient to keep shipping lanes open, but could also pose an offensive threat to other coastal nations.[10] Furthermore, suppose that offense is more effective than defense, meaning "that it is easier to destroy the other's army and take its territory than it is to defend one's own."[11] The security dilemma facing the decision maker is that a spiraling arms race or war can result despite all states' preferences for other outcomes.

Herz explained the "security dilemma" as a result of the "anarchic" situation "where groups live alongside each other without being organized into a higher unity. ... Since none [of the groups] can ever feel entirely secure in such a world of competing units, power competition ensues, and the vicious circle of security and power accumulation is on."[12] Evera discusses the "cult of the offensive" in the decades before World War I, which is the attitude that "offensive solutions to security problems were the most effective."[13] He argues that the "cult of the offensive was a major underlying cause of the war of 1914",[14] and presents this as an example that an "offense-dominant world is more dangerous".[15]

While the discussions by Herz and by Evera are important and convincing, we will place the security dilemma in a different—but still very broad—context that is conducive to the formulation and evaluation of strategy. Our focus will be on how the strategic decision maker can model and manage the severe uncertainty of the available information.

The security dilemma can be understood in the context of what we will call an *innovation dilemma.*[16] This dilemma arises often in choosing between new, innovative but less familiar technology, and older, less ambitious but more thoroughly understood technology. Hence the name, innovation dilemma, which becomes a metaphor and prototype of a broad class of dilemmas. Consider a choice between two options, where the first option is judged to be better in the outcome than the second option, but the first option is far more uncertain than the second and could lead to a much worse outcome. The dilemma is in choosing between a putatively better option that is much riskier, and a putatively worse but less uncertain option.

The security dilemma is—in many situations—an instance of the innovation dilemma due to the great uncertainty surrounding the intentions and capabilities of a state's potential adversaries. The estimate that the adversary is arming with the intention to attack may be credible, indicating the need to arm or preemptively attack in response. However, by taking the nominally preferred choice of rapid armament or offensive action, a state incurs the risk of a spiraling arms race or extended war as both the stakes and the uncertainties grow. A dilemma arises if what looks like the best alternative, based on available evidence, is also the most prone to error and could lead to loss that exceeds the outcomes of other alternatives. When facing an innovation dilemma one must recognize that the situation is not characterized only by one's estimates and assessments, but also by the unknown degree of error of those estimates and assessments. The innovation dilemma arises from the gap between what the analyst *does know*—the available evidence—and what the analyst *needs to know*—the actual intentions and capabilities of the adversary. This information gap must be managed in dealing with an innovation dilemma. In the next section we will discuss a strategy-selection response to the innovation dilemma.

Not all security problems are innovation dilemmas. History presents examples where offensive actions, declarations and intentions of an adversary were clear and unambiguous, and where only wishful thinking could allow one to delay one's response to the pending attack. Likewise there are examples where the pacific intentions of past or potential adversaries are also clear and certain. There are also situations where—despite uncertainties—the indicated action is both purportedly better and less uncertain than alternative actions. In such situations the assessments are reliable, or relatively so, and the response that is indicated by a direct reading of the evidence is clearly the correct one. An innovation dilemma arises when uncertainty is rampant and when what seems to be the best strategy is also the most prone to error and could lead to worse outcomes than alternative strategies.

Guns or butter

The "guns or butter" metaphor refers to the trade off between investment in national defense, or investment in civilian consumer goods and infrastructure. Given a finite budget, allocation to one category is at the expense of allocation to the other.

The choice of the allocation between "guns" and "butter" need not be an innovation dilemma. For example, Brands notes that "[t]he long-standing U.S. defense umbrella over the Western Hemisphere has afforded Brazil a degree of free security from external threat. Similarly, Washington's policing of the global commons has allowed Brazil to trade around the world without building a Navy capable of protecting that commerce."[17]

A guns-or-butter innovation dilemma can arise if development of human capital is highly uncertain. For example, it is widely acknowledged, in both democratic and totalitarian societies, that investment in at least some degree of public health and education is an essential element of national security by enhancing the capability and motivation of the citizenry. However, uncertain long-term effectiveness of health and education programs can lead to disastrous security outcomes resulting from devoting resources to ineffective human development rather than to direct military expenditure. What looks like the better investment—in human capital—is also highly uncertain and risky if the civilian investment could be ineffective, leading to deficits in both military and human assets. The choice between the different investment options requires a method for balancing goals and uncertainties, as we will illustrate later.

Armor or intel

The "armor or intelligence" metaphor derives from the trade off, given a limited budget, between the ability to apply force, and the ability to identify threats and targets for that force. Neither alone would be effective. More generically, the metaphor refers to the trade off between different but complementary military capabilities. For example, Gordon and Sollinger write that "the Army's essential problem is the changing relationship between air and ground forces at the high end of the conflict spectrum, especially the appeal that stand-off (usually air-delivered) precision munitions have to risk-averse decisionmakers."[18] The attractiveness of airpower over landpower was illustrated in the Israeli "Pillar of Defense" operation in Gaza (14–21 November 2012). Massive landpower was deployed at the border, but operations were terminated after 8 days of precise aerial munition and naval artillery attack without land action. As Milevski explains in a different context, "Landpower exclusively may take and exercise control", but "Landpower, of all tools of power, faces the greatest impediments, risks, and dangers in its use."[19] Critics of Israel's cease-fire pointed out that Hamas retained considerable assets—rockets and launchers hidden in civilian areas—that could be destroyed only by invasion. The response to these critics was that invasion would entail significant civilian and military casualties and international condemnation.

Choosing between the following two strategies, motivated by the Israeli experience, will illustrate an armor-or-intel innovation dilemma. On the one hand, massive investment in aerial delivery systems and instrumented intelligence sources, as well as sensor capabilities for threat detection and munitions control, would enable effective focussed use of aerial and artillery power. Landpower is needed only in a supporting role. We will refer to this strategy concisely as "aerial intel and delivery". This strategy would leverage the strong existing Israeli hi-tech capabilities. On the other hand, extensive landpower with supporting airpower are essential for defense and control of territory because Israel is a tiny country with almost no strategic depth separating major civilian populations from international borders, and is thus extremely vulnerable to invasion. We will refer to this as the landpower strategy.

An Israeli strategist might reason as follows in selecting between these two strategies, drawing on the experience of operations in Lebanon[20] and Gaza[21] over the past 7 years. The major security challenges in coming years arise from missile bombardment of Israeli cities and towns by non-state actors. The threat of land invasion by a national army is small though not negligible. Consequently, the preferred response by risk-averse elected officials, and in light of international constraints, focusses on neutralizing incoming missiles, extensive intelligence on the adversaries' capabilities, and pin-point aerial capability for eliminating enemy assets. In short, the best current estimates indicate a clear preference for the aerial intel and delivery strategy over the landpower strategy.

The innovation dilemma results because the best current estimates of future security challenges are highly uncertain. The fluid nature of geo-politics in the region can cause rapid change in the dominant security challenges. Degradation of conventional landpower would be disastrous in the case of a major theater war with a coalition of regional states. Indeed, under-development of landpower could even induce a traditional war as the perceived deterrence erodes, even though the current horizon of contingencies makes such a scenario unlikely. In short, the innovation dilemma is that the most reasonable strategy—aerial intel and delivery—is also the riskiest given the great uncertainty about future political and military developments in the immediate region and beyond. We will return to this example in the next section and illustrate a method of analysis based on the concept of robustness.

Robust-Satisfying Methodology for Selecting Strategy

The successful response to uncertainty is to face it, grapple with it, exploit it, restrain it, but never hope to abolish it. Uncertainty is inevitable.

The pervasiveness of uncertainty has profound implications for what it means to "do one's best" in many areas, including military strategy. The decision methodology that could be called "outcome-optimization" first identifies the best available information, understanding, and insight—collectively called "models"—and then chooses the option whose outcome is predicted to be best based on these models. The models may include assessments of uncertainty, either explicitly as numerical probabilities or implicitly as judgments of likelihoods or propensities.

We will claim that outcome-optimization is an inadequate methodology for decision-making when facing an innovation dilemma. Instead, we will advocate the decision methodology of robustly satisfying outcome requirements. The basic idea is to first identify outcomes that are essential, and then to choose the alternative that will achieve those critical outcomes over the greatest range of future surprise. We use our models in two ways. First, to assess the putative desirability of the alternatives, and second, to evaluate the vulnerability to error of those alternatives. The robust-satisfying strategy is the one with maximal robustness to error while satisfying the critical requirements. In other words, what is optimized is not the predicted quality of the outcome, but rather the immunity to error and surprise. The outcome will be satisfactory, though not necessarily optimal, over the greatest range of future deviations from our current understanding.

Colin Gray expresses something very close to this idea when he writes:

> You cannot know today what choices in defense planning you should make that will be judged correct in ten or 20 years' time. Why? Because one cannot know what is unknowable. Rather than accept a challenge that is impossible to meet, however, pick one that can be met well enough. Specifically, develop policy-makers, defense planners, and military executives so that they are intellectually equipped to find good enough solutions to the problems that emerge or even erupt unpredictably years from now.[22]
>
> The gold standard for good enough defense planning is to get the biggest decisions correct enough so that one's successors will lament 'if only . . . ' solely with regard to past errors that are distinctly survivable.[23]

The goal of the robust-satisfying decision methodology is to reliably achieve specified objectives, as distinct from attempting to achieve optimal outcomes whatever they might be. Freilich describes a closely related idea in analyzing Israeli formulation of military strategy in Lebanon:

> We have thus adopted a different criterion of success as the measure of a DMP [decision making process]: not the quality of the outcome, but the degree to which decision makers achieved their objectives. The central argument is not that Israel would have achieved better outcomes had the process been better, but that the prospects of it actually achieving its objectives would have increased significantly.[24]

Robustness to uncertainty, or simply "robustness," is central to the methodology that we are describing. A strategy is robust to uncertainty if the specified outcome requirements are achieved even if the situation develops in ways that differ greatly from our anticipations. A strategy is highly robust if essential goals are achieved despite great surprise or large error of understanding. Low robustness means that the strategic goals may be jeopardized if the situation deviates even slightly from the model-based predictions.

Robustness to uncertainty is the focus of many decision theories. The concept of robustness upon which we will focus depends on the idea of non-probabilistic uncertainty. Knight[25] distinguished between 'risk' based on known probability distributions and 'true uncertainty' for which probability distributions are not known. Non-probabilistic uncertainty results from our ignorance of the past, of the present and especially of the future. Lempert, Popper and Bankes, working in the spirit of Knightian uncertainty, have developed "Robust Decision Making" that uses extensive computational capability to explore scenario uncertainties for long-range planning and policy analysis.[26] Similarly, Ben-Tal and Nemirovski[27] are concerned with uncertain data within a prescribed uncertainty set, without any probabilistic information. Likewise Hites *et al.*[28] view "robustness as an aptitude to resist to 'approximations' or 'zones of ignorance'", an attitude adopted also by Roy.[29] We also are concerned with robustness against Knightian uncertainty, and we will describe a strategy-selection methodology based on information-gap decision theory.[30]

Info-gap theory provides quantifications of Knightian uncertainty and robustness, and specifies a systematic decision methodology for satisfying critical requirements.[31] Info-gap theory has been applied to decision problems in many fields, including various areas of engineering,[32,33,34] biological conservation,[35] economics,[36,37] medicine,[38] homeland security,[39] public policy[40] and more[41]. Info-gap robust-satisfying has been discussed non-technically elsewhere.[42,43,44]

Three components make up an info-gap robust-satisfying decision. The first component is our information, understanding, and insight about the relevant situations, referred to as our "models". Second, we specify the goals that must be achieved, without which the outcome is not acceptable or not "distinctly survivable." Third, we identify those aspects of the first two elements—the models and the outcome requirements—that are uncertain, about which we are or might be wrong or ignorant. For example, we might mis-estimate the rate of future increase in enemy capabilities resulting from future technologies. Or, we don't know what events will hinder or delay completion of critical missions. Or, we don't know what international political developments will alter domestic political goals or constraints.

These three components—models, requirements, and uncertainties—are combined in assessing the robustness of any proposed strategy. The robustness of a specified strategy is the greatest uncertainty that can be tolerated without violating the outcome requirements. The robustness is the greatest degree of error in the models and requirements up to which all realizations do not violate the requirements (whose initial specification may err).

For simplicity of exposition, the example we will consider involves only a single outcome requirement. The info-gap robust-satisfying procedure is readily applied to multiple requirements, even when they are conflicting. For example, the requirement of few casualties in the home civilian population may conflict with requiring few casualties in the enemy civilian population. The robustness varies as these two requirements vary, enabling the analyst to explore the feasibility of different levels of trade off between them.

Strategy selection for an armor-or-intel innovation dilemma: Simplified example

We consider a simplified armor-or-intel innovation dilemma in order to illustrate the robust-satisfying decision procedure and to identify its distinctive traits. We will examine a plausible but hypothetical scenario. Different judgments might be made in a real-life situation.

Our understanding of the situation—*the model*—is that the enemy has two alternative modes of attack. The much more likely mode is to support informal non-state actors engaging in frequent but fluctuating missile bombardment of civilian populations. Large arsenals can be provided to these non-state actors, who have high motivation and ability to cause injury and damage and to seriously disrupt civilian life. The much less likely mode of attack is conventional war with land forces and supporting air power. Major injury and damage would result from unrestrained conventional war.

The *critical requirement* is to maintain, in the civilian population, a sense of personal security and normality in daily life. This is operationalized by requiring a low level of loss of life, injury or damage to property.

Four issues are subject to severe *uncertainty*. First, the likelihood of conventional war is small but not negligible and it is imprecisely known. Neighboring countries maintain substantial standing armies with offensive capabilities. Future geo-political developments could quickly change the likelihood of war. Second, the future missile range, payload, accuracy and quantity employed by the non-state actors will improve at an unknown rate. Third, instrumented intelligence can greatly enhance the effectiveness of weapons systems. However, as Tomes notes, "Information dominance requires deep knowledge of the adversary, the operating environment and the nature of the potential conflict, not just data points representing targets on a computer screen."[45] The extent to which instrumented intelligence can provide the needed deep knowledge is highly uncertain. These first three uncertainties relate to the model. The fourth uncertainty is that the civilian population may, in the future, become less tolerant to loss of life, injury or damage. Thus the critical requirement is uncertain. The critical requirement may also be uncertain due to political conflict arising over procurement and deployment of new technology.[46]

Having outlined the model, the critical requirement, and the uncertainties, we now specify two alternative strategies, and subsequently assess their robustness.

The first strategy, that we earlier called aerial intel and delivery, will be denoted AID. AID is designed to drastically reduce the disruption of civilian life from non-state missile bombardment by continuous interdiction of missile attack and by targeted elimination of enemy assets. Supported by solid land capability, the model predicts that this strategy plausibly provides acceptably low loss of life, injury or damage in response to either enemy mode of attack. Ignoring uncertainty for the moment, the model indicates that this strategy would be acceptable.

The second strategy, that we earlier called the landpower strategy and will now denote LP, is primarily designed to repulse a conventional invasion and to quickly bring the conflict into enemy territory. This strategy is less effective than aerial intel and delivery against low-level non-state missile attack. Major landpower can be employed to eliminate such activity by invasion and control of territory, but the threshold for action is necessarily rather high. Consequently our model predicts that a greater level of loss of life, injury or damage is the plausible outcome of LP. Again ignoring uncertainty for the moment, our model indicates that LP is less acceptable than AID. That is, if we knew the model to be correct, we would prefer AID over LP. AID would be the preferred strategy based on the outcome-optimization methodology discussed earlier.

We are now in a position to evaluate the robustness to uncertainty of each strategy, for satisfying the critical requirement. The example will demonstrate four general and inter-related conclusions that we summarize now and elaborate later. First, predicted outcomes are not reliable for strategy selection. Our models are quite likely wrong, so model-based predictions may err greatly and thus are not a reliable basis for prioritizing the available strategies. Second, only worse-than-predicted outcomes can be robustly anticipated. More specifically, the quality of the outcome that is required trades off against robustness to uncertainty: one is less robust when requiring a more ambitious outcome. Third, the strategy that is preferable, based on its predicted outcome, may in fact be less robust than the alternatives for achieving an acceptable outcome. When this holds, the robust prioritization of strategies may differ from the outcome-optimization prioritization. We will see that this reversal of preference may arise in an innovation dilemma. Fourth, the info-gap robust-satisfying analysis is a conceptual framework for deliberation and selection of strategy. The analysis identifies and clarifies the implications of the central judgments that must be made.

Predicted outcomes are not reliable for strategy selection. Consider aerial intel and delivery. Our model leads us to anticipate some level of loss and disruption of civilian life. We recognize serious uncertainties in the model, so actual loss could plausibly be greater and AID would be an acceptable strategy only if we are willing to accept greater loss than nominally indicated. The situation is the same for landpower. Our model predicts some level of loss but, due to uncertainty, LP would be an acceptable strategy only if greater loss is acceptable.

We now reach our first general conclusion. The preference between AID and LP cannot depend only on the predicted outcomes of these strategies, because these predictions are highly uncertain and therefore have little or no robustness. The prioritization of AID and LP depends not only on the model-based predicted outcomes, but also on how much worse an outcome we are willing to accept.

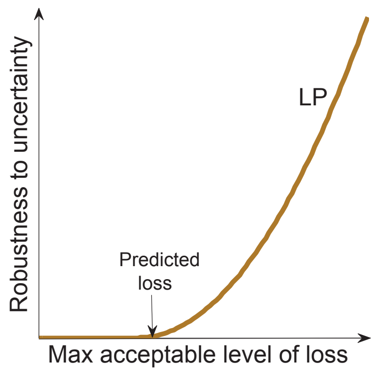

Figure 1: Schematic robustness curve for the LP strategy.

Robustness trade off of the LP strategy (fig. 1). Now return to the LP strategy and ask how vulnerable it is to error. Massive landpower, applied with unflinching determination, provides a decisive response to informal non-state missile attack over a wide range of technological and organizational capabilities. It also provides decisive deterrence or response to conventional war. Thus LP will provide adequate response even if the current estimates of the likelihood of war, or of enemy missile capabilities or morale err substantially. In other words, LP is highly robust to the first three uncertainties. The fourth uncertainty concerns the level of loss of life, injury and disruption that the domestic civilian population is willing and able to tolerate. If that tolerance is substantially greater than the model-based predicted loss and disruption for LP, then we can be fairly confident that LP would be acceptable regardless of the future likelihood of war or the future technology or organizational factors of the non-state actors or future civilian attitudes. In short, LP is highly invulnerable—highly robust—to the relevant uncertainties, provided that public tolerance significantly exceeds the predicted loss for applying the LP response. (Recall that, in this simplified example, we are not considering the political or international aspects of invasion and control of territory. Our outcome requirement only addresses domestic attitudes.)

The robustness trade off for the LP strategy is illustrated schematically in fig. 1. The figure will help clarify the trade off concept even though it is not the result of any numerical calculation. The horizontal axis represents the greatest acceptable level of loss. Points to the right on the horizontal axis depict large public tolerance to loss, disruption and injury, while points to the left depict low tolerance. The vertical axis represents the robustness against uncertainty and surprise. The predicted level of loss has the lowest robustness: the greatest vulnerability to surprise. Actual loss could easily exceed the model-based prediction because the models are highly uncertain. The robustness to error increases as the acceptable level of loss increases. Thus the robustness curve has positive slope, reflecting the trade off: greater robustness to error in the models is obtained only by accepting greater potential for loss. Stated differently, the trade off asserts that very demanding requirements (requiring very low loss) have low robustness against error; less demanding requirements (larger acceptable loss) are more robust.

Robustness trade off of the AID strategy (fig. 2). While the AID strategy includes solid land

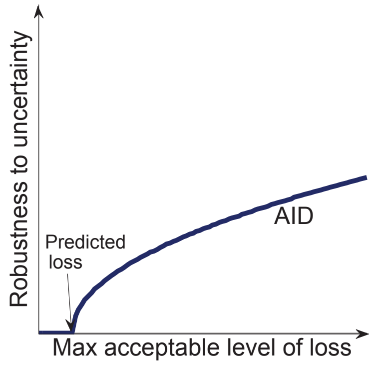

Figure 2: Schematic robustness curve for the AID strategy.

capability, it is not designed primarily as a response to conventional war. If war occurs, AID will pay a higher price than LP. AID has low tolerance to error in the model's prediction of the low likelihood of conventional war. Furthermore, in our hypothetical example, AID depends on technologies that are either new or are currently being developed. The performance of AID is uncertain because experience with these technologies is limited and because they provide limited insight into the organization and motivation of the enemy. For instance, how successful AID would be in response to multiple targets is unclear. Likewise, the service life in the field of AID technology is poorly known. Similarly, how well AID would undermine the morale or organizational resilience of the non-state enemy is poorly known. In short, the AID strategy is quite vulnerable to error in the model. As illustrated in fig. 2, the robustness of AID to uncertainty gradually increases as the acceptable level of loss increases. The increase is gradual because of AID's vulnerabilities to errors in the model. We summarize this by saying that AID's robustness to uncertainty trades off rather strongly against the level of acceptable loss.

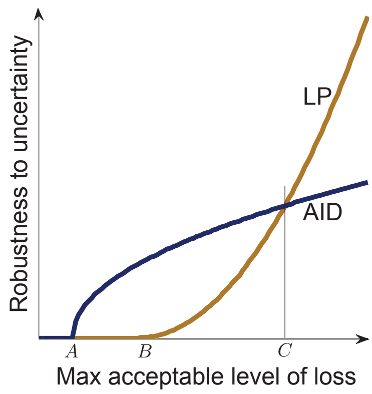

Figure 3: Schematic robustness curves showing preference reversal between LP and AID.

Potential for preference reversal (fig. 3). The choice between landpower and aerial intel and delivery, in the plausible but hypothetical scenario that we have described, is an innovation dilemma. LP is predicted, based on our best understanding and information, to entail greater loss and disruption of civilian life than AID (compare points B and A in fig. 3). However, AID is more vulnerable to uncertainty than LP. AID's robustness trades off more rapidly against acceptable loss than LP's (compare the slopes in fig. 3). The robustness curves for AID and LP cross each other because the AID curve has better predicted outcome (starts further to the left) but has worse robustness trade off (lower slope). This intersection of the robustness curves is the graphical representation of the innovation dilemma.

We observe here a potential reversal of preference between AID and LP, which is an illustration of the third general conclusion regarding innovation dilemmas. AID is predicted to entail lower loss and disruption than LP (point A is to the left of B in fig. 3). So, based on predicted losses, AID is preferred over LP. However, predicted outcomes are highly uncertain, and robustness trades off against acceptable loss (positive slopes in fig. 3). If the acceptable loss is in the lower range, anywhere from A to C, then AID is more robust than LP so AID would be preferred over LP. However, if the public is more resilient and tolerant of damage, loss and injury, anywhere to the right of point C, then LP is more robust than AID. A given strategy (AID or LP) has two attributes that are depicted in fig. 3: its predicted loss (the horizontal intercept) and its sensitivity to error in the models (the slope). These two attributes indicate that the robust-satisfying preference is for AID over LP at lower levels of acceptable loss, while the robust-satisfying preference is for LP over AID at less demanding requirements (greater acceptable loss). The dilemma that initially faces the decision maker is that AID is purportedly better, but LP is less vulnerable to error. The dilemma is resolved by the robust-satisfying methodology of prioritizing the options according to their relative robustnesses at the required outcome.

Basis for deliberation. The robust-satisfying analysis does not determine a unique choice, unlike the outcome-optimization analysis that points to a unique predicted best decision. The info-gap robust-satisfying methodology provides a framework for deliberation and decision. It identifies the main judgments that must be made and the implications of different assessments. In comparing strategies, judgments must be made not only of relative outcomes, but also of relative robustnesses to error. Looking at fig. 3 we see that the judgments must focus on two main aspects of each proposed strategy: the predicted consequence (the horizontal intercept), and the robustness to error of the prediction (the slope). Furthermore, judgment must be made of the critical or required outcome, in comparison to the robust range of outcomes for each option. Determining which option is robust-preferred depends on consideration of all these factors: predicted outcomes, robustness trade off, and outcome requirements.

Extensions of the armor-or-intel example

The above example illustrates the robust-satisfying procedure for prioritizing strategies in response to an innovation dilemma, and demonstrates four generic properties of the analysis. The example is not to be understood as a comprehensive analysis, and we now briefly mention several extensions. A full analysis would apply the robust-satisfying procedure to all aspects of the situation.

A more realistic analysis would need to consider the multiplicity of requirements typically facing the strategy analyst. We have only considered civilian loss of life, injury and damage. The analyst also needs to consider the implications for international relations of the choice of strategy. In particular, the AID and LP strategies are likely to have different impacts on non-combatant populations, with various international legal and political implications. Considerations of deterrence beyond the immediate conflict may be relevant. The use of particular technologies may have implications and impacts that must be considered. Other considerations may arise as well.

We have only considered two rather stylized threat categories. In practice it is necessary to formulate these threats in greater detail, and to adjust the uncertainties accordingly. There are also likely to be more than just two categories of threats. The available responses are also likely to be more nuanced and numerous than our example assumed.

We have not explicitly considered the temporal dimension. The relative importance of both threats and responses can depend strongly on how quickly they might arise or become available, respectively. Global strategic implications may emerge more slowly than regional responses, and may therefore weigh differently in the analysis. In addition, it may be possible to introduce an element of adaptivity in the strategy, allowing it to evolve in response to the evolving situation. The question at the planning stage is what guidelines should direct the adaptive revision of strategy. Adaptivity of response may also be relevant when employing an emerging technology whose full potential is unknown or unproven during the initial analysis.

Finally, some elements of the situation may be amenable to quantitative analysis, using mathematical models and numerical data. Such an analysis can be integrated with the language-level analysis that we have described.

Conclusion

Of all governmental activities, military activities are perhaps the most extensively analyzed and planned. But war and uncertainty are inseparable, and "The best-laid schemes o' Mice an' Men, Gang aft agley".[47]

We have discussed the info-gap robust-satisfying methodology for formulation and analysis of strategy when facing severe uncertainty in the form of an innovation dilemma. It often happens that the best information and understanding suggest that one option is more propitious than another, but that the putatively better option is also more uncertain and riskier than the other option. This is paradigmatic for the choice between an innovative new strategy or a more standard state of the art. We have shown that innovation dilemmas arise in many security challenges.

The response to an innovation dilemma is to robustly satisfy critical outcome requirements, rather than to choose the option that is predicted to have the best outcome. Under severe uncertainty, predicted outcomes have little or no robustness against error in the models upon which those predictions are based. Furthermore, only worse-than-predicted outcomes can be robustly anticipated to occur. The prioritization of strategies should be based on their immunity to error. A strategy that will achieve essential goals over a wider range of contingencies is preferred over a strategy that is less robust to surprise. When facing severe uncertainty, one should optimize the robustness against ignorance, uncertainty and surprise, while satisfying critical and essential goals. The info-gap robust-satisfying procedure is a method for analysis and deliberation in the selection of strategy.

Notes

1. Churchill, Winston S., 1950, *The 2nd World War,* vol. 4, *The Hinge of Fate,* The Houghton Mifflin Co., New York, p.831.
2. Clausewitz, Carl von, 1832, *On War,* Trans. by Michael Howard and Peter Paret, abridged by Beatrice Heuser, Oxford University Press, Oxford, Book 1, chap. 3, p.46.
3. Ibid., Book 1, chap. 1, article 20, p.26.
4. Herbig, Katherine L., 1989, Chance and Uncertainty in *On War,* in Michael Handel, ed., *Clausewitz and Modern Strategy,* Frank Cass, London, pp.95–116. See p.104.
5. Ibid, p.102.
6. Ibid, p.104.
7. Myers, Steven Lee, In fog of war, rift widens between U.S. and Pakistan, New York Times, November 27, 2011, http://www.nytimes.com/2011/11/28/world/asia/pakistan-and-united-states-bitter-allies-in-fog-of-war.html?ref=world
8. Tomes, Robert R., 2012, An historical review of US defense strategy from Vietnam to operation Iraqi freedom, *Defense & Security Analysis,* 28(4): 303–315, especially p.311.
9. Jervis, Robert, 1978, Cooperation under the security dilemma, *World Politics,* vol.30, no.2, pp.167–214.
10. Ibid, p.170.
11. Ibid, p.187.
12. Herz, John H., 1950, Idealist internationalism and the security dilemma, *World Politics,* Vol. 2, No. 2, pp. 157–180. See p.157.
13. Evera, Stephen Van, 1984, The cult of the offensive and the origins of the first World War, *International Security,* Vol. 9, No. 1, pp. 58–107. See p.58.
14. Ibid, p.105.
15. Ibid, p.106.
16. Ben-Haim, Yakov, Craig D. Osteen and L. Joe Moffitt, 2013, Policy dilemma of innovation: An info-gap approach, *Ecological Economics,* 85: 130–138.
17. Brands, Hal, 2010, Dilemmas Of Brazilian grand strategy, Strategic Studies Institute Monograph, p.10. http://www.StrategicStudiesInstitute.army.mil

18. Gordon IV, John and Jerry Sollinger, 2004, The Army's dilemma, *Parameters,* Summer 2004, pp.33–45. See p.43.
19. Milevski, Lukas, 2012, *Fortissimus inter pares:* The utility of landpower in grand strategy, *Parameters,* Summer, 2012. pp.6–14. See p.14.
20. 2nd Lebanon War, 12 July to 14 August 2006.
21. Operation Cast Lead, 27 December 2008 to 17 January 2009, and Operation Pillar of Defense, 14 to 21 November 2012.
22. Gray, Colin S., 2010, War—Continuity in Change, and Change in Continuity, *Parameters,* Summer, 2010, pp.5–13. See p.6.
23. Ibid, p.9.
24. Freilich, Charles D., 2012, Israel in Lebanon—Getting It Wrong: The 1982 Invasion, 2000 Withdrawal, and 2006 War, *The Israel Journal of Foreign Affairs,* 6(3): 41–75. See p.69.
25. Knight, F.H., 1921, *Risk, Uncertainty and Profit,* Hart, Schaffner and Marx. Re-issued by Harper Torchbooks, New York, 1965.
26. Lempert, Robert J., Steven W. Popper and Steven C. Bankes, 2003, *Shaping the Next 100 Years: New Methods for Quantitative, Long-Term Policy Analysis,* RAND Corp., Santa Monica, CA.
27. Ben-Tal, A. and A. Nemirovski, 1999, Robust solutions of uncertain linear programs, *Oper. Res. Lett.,* 25, 1–13.
28. Hites, R., Y. De Smet, N. Risse, M. Salazar-Neumann and P. Vincke, 2006, About the applicability of MCDA to some robustness problems, *Eur. J. Oper. Res.* 174: 322–332. See p.323.
29. Roy, B., 2010, Robustness in operational research and decision aiding: A multi-faceted issue, *Eur. J. Oper. Res.* 200: 629–638.
30. Ben-Haim, Yakov, 2006, *Info-Gap Decision Theory: Decisions Under Severe Uncertainty,* 2nd edition, Academic Press, London.
31. Info-gap theory also supports a decision strategy called opportune windfalling that is complementary to robust satisfying. Opportune windfalling seeks to exploit favorable surprises, while robust satisfying attempts to protect against pernicious contingencies. We won't discuss opportune windfalling.
32. Chinnappen-Rimer, S. and G.P. Hancke, 2011, Actor coordination using info-gap decision theory in wireless sensor and actor networks, *International Journal of Sensor Networks,* 10(4): 177–191.
33. Harp, Dylan R. and Velimir V. Vesselinov, 2013, Contaminant remediation decision analysis using information gap theory, *Stochastic Environmental Research and Risk Assessment,* 27(1) pp.159–168.
34. Kanno, Y. and I. Takewaki, 2006, Robustness analysis of trusses with separable load and structural uncertainties, *International Journal of Solids and Structures,* 43(9): 2646–2669.
35. Burgman, Mark, 2005, *Risks and Decisions for Conservation and Environmental Management,* Cambridge University Press, Cambridge.
36. Ben-Haim, Yakov, 2010, *Info-Gap Economics: An Operational Introduction,* Palgrave, London.
37. Knoke, Thomas, 2008, Mixed forests and finance - Methodological approaches, *Ecological Economics,* Volume 65(3): 590–601.
38. Ben-Haim, Yakov, Nicola M. Zetola and Clifford Dacso, 2012, Info-gap management of public health policy for TB with HIV-prevalence, *BMC Public Health,* 12: 1091. DOI: 10.1186/1471-2458-12-1091, URL: http://www.biomedcentral.com/1471-2458/12/1091
39. Moffitt, L. Joe, John K. Stranlund, and Barry C. Field, 2005, Inspections to avert terrorism: Robustness under severe uncertainty, *J. Homeland Security and Emergency Management,* vol. 2, no. 3. http://www.bepress.com/jhsem/vol2/iss3/3

40. Hall, Jim W., Robert J. Lempert, Klaus Keller, Andrew Hackbarth, Christophe Mijere, and David J. McInerney, 2012, Robust climate policies under uncertainty: A comparison of robust decision making and info-gap methods, *Risk Analysis,* 32 (10): 1657–1672.
41. http://info-gap.com
42. Ben-Haim, Yakov, 2012, Doing our best: Optimization and the management of risk, *Risk Analysis,* 32(8): 1326–1332.
43. Ben-Haim, Yakov, 2012, Why risk analysis is difficult, and some thoughts on how to proceed, *Risk Analysis,* 32(10): 1638–1646.
44. Schwartz, Barry, Yakov Ben-Haim, and Cliff Dacso, 2011, What Makes a Good Decision? Robust Satisficing as a Normative Standard of Rational Behaviour, *The Journal for the Theory of Social Behaviour,* 41(2): 209–227.
45. Tomes, Robert R., 2012, *op.cit.,* p.309.
46. Jones, Christopher M. and Kevin P. Marsh, 2011, The politics of weapons procurement: Why some programs survive and others die, *Defense & Security Analysis,* 27(4): 359–373, p.372.
47. Burns, Robert, 1785, To a Mouse, on Turning Her Up in Her Nest with the Plough.

Figure Captions

Figure 1. Schematic robustness curve for the LP strategy.
Figure 2. Schematic robustness curve for the AID strategy.
Figure 3. Schematic robustness curves showing preference reversal between LP and AID.