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DEFINING ENGINEERING SYSTEMS: INVESTIGATING NATIONAL MISSILE DEFENSE

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Introduction

The MIT Engineering Systems Division is currently building its intellectual framework. There is not yet consensus within ESD as to which tools and methods are central to the nascent engineering systems approach; which questions it should address; or the extent to which qualitative approaches should be incorporated into it. The goal of this paper is to sharpen the debate by presenting multiple analyses of a single engineering system. Presenting varying perspectives illuminates issues such as:

- What types of questions should engineering systems practitioners ask when analyzing problems?
- Which tools are fundamental, which are peripheral, and which lie outside its purview?
- Is there a trade-off between the analytical rigor of different tools and the degree to which they can address questions the approach considers important?
- Does this approach suggest generalizable principles for analyzing engineering systems?

This paper uses national missile defense (NMD) as the analytical vehicle for this approach. By any definition, NMD is an engineering system. Moreover, the complexity of NMD facilitates the framing of analyses on multiple levels, and provides a mechanism for exploring the ramifications of different potential definitions of "engineering systems" as a discipline. Finally, the issue is policy-relevant. The United States is currently deciding how to build and deploy NMD; the choice of system architectures may have important cost, foreign policy, military readiness, and domestic political ramifications. While there is considerable descriptive information about system components, there is little hard data in the open literature regarding system performance and costs. This paper draws upon the available literature, while making estimates where necessary.

It is important to state at the outset that this paper assumes two key (and often-disputed) points. First, it is assumed that technologies under development will be feasible. Second, it is assumed that adversaries may build intercontinental ballistic missiles and equip them with weapons of mass destruction (in addition to Russia and China, who already possess them). The paper therefore should be read as a vehicle for exploring issues at the heart of engineering systems rather than as a policy analysis.

Outline

This body of this paper consists of five perspectives on the NMD problem:

- Technical description and "what-if" probabilistic analysis
- CLIOS representation

- Game theory
- Systems analysis
- Politics of U.S. weapons procurement

The paper concludes with implications drawn from the NMD case for engineering systems as a discipline.

Technical Description and Probabilistic Analysis

Technical Description

Intercontinental ballistic missiles require roughly thirty minutes to reach their targets. For the purpose of thinking about missile defenses, flight time is divided into three phases: a boost phase lasting three to five minutes; a midcourse phase lasting roughly twenty-five minutes, when the missile coasts unpowered through inner space; and a re-entry phase lasting less than one minute where the missile finishes its descent onto its target. During the boost phase, the missile's engines are firing, so that its heat signature is easily observed and tracked; moreover, while the engines are still attached, the missile is a larger target. During the midcourse phase, the warheads (and any decoys) separate from the engines. Distinguishing between warheads and decoys may be a challenge for defensive systems. During the re-entry phase, the atmosphere separates the decoys from the warheads, but the warheads' speed, and the corresponding short duration of the re-entry phase, makes it difficult for defenses to successfully intercept targets.[1]

Missile defenses consist of several components:

- Early warning systems that detect launches and project the general direction of missile flight. Currently, the United States detects launches with geostationary satellites using infra-red sensors (the Defense Support Program or DSP) and a group of early warning radars located in the United States and Europe.
- Tracking radars that project an object's trajectory sufficiently for it to be intercepted, and that could possibly distinguish between warheads and decoys. The United States plans to upgrade its early warning radars to give them tracking capabilities useful for missile defense and to build several additional high-frequency (X-band) radars specifically designed for missile defense. Some NMD designs also include satellites (called the Space-based infrared system or SBIRS-low) to assist with tracking and warhead discrimination.
- Interceptors that destroy warheads or decoys. Several possible interceptors have been discussed and are in various stages of research and development, including missiles that would intercept targets during the midcourse phase (ground-based or sea-based), sea-based boost-phase interceptor missiles, lasers (either airborne or space-based), or space-based kinetic kill vehicles.

[1] Presentation by Prof. Daniel Hastings, "NMD: Science, Technology, and Policy," October 22nd, 2001; Sessler et al, "Countermeasures," Union of Concerned Scientists/MIT Security Studies Study Group, April 2000, page 19.

- Battle management systems that integrate the sensor information, determine where and when to fire interceptors, communicate with launch sites and commanders, and decide whether interception has been successful.[2]

Architectures Proposed by the Clinton and Second Bush Administrations

The Clinton Administration proposed an architecture built around ground-based interceptors that would evolve incrementally over time. The initial system (the "C-1" architecture) would consist of 100 interceptors based in Alaska, upgrades to the early warning radars, and a single, westward-facing, X-band radar. The initial system would therefore have greater capability of defending the United States from missiles launched eastward by countries such as North Korea, China, and Russia than from missiles launched westward toward the U.S. Upgrades over time ("C-2" and "C-3" architectures) would add eight more X-band radars, 150 more interceptors including a second site in North Dakota, and SBIRS-low.[3]

This proposal had certain advantages, as well as risks. Advantages of the design included relatively low cost (roughly \$20-30 billion for the C-1 system and \$50-60 billion for the full C-3 capability), the potential to protect the United States from launches from any country, and the possibility that the system could comply with the 1972 Antiballistic Missile Treaty. At the same time, the program faced several technological risks. By picking a technical path with the aim of complying with the ABM treaty, the program ruled out alternate approaches, posing the risk of locking the nation into a single, unproven technology. Given that this path used mid-course interceptors, it also required the successful development of technologies to discriminate between decoys and real warheads.[4]

The second Bush Administration has re-opened the issue of NMD architecture. To date, the Defense Department has not settled on a design for the system, and rather has broadly expanded its research and development of NMD technologies.[5] Such an approach is more likely to limit technology risks than did the Clinton Administration's. At the same time, it will certainly require greater research and development costs, and may require higher procurement costs, as will be discussed below. Reconsidering the design also may slow the development of a defense system, but a better system developed more slowly may be more valuable than a rapidly-developed but immature one. Moreover, the Administration could not adopt this approach without either renegotiating or abandoning

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[2] See UCS/MIT, Countermeasures, pages 21-29; Federation of American Scientists' Web site http://www.fas.org/ssp/bmd/index.html, for more detailed descriptions of system components
[3] UCS/MIT, Countermeasures, pages 19-24.
[4] UCS/MIT Countermeasures, page 25; U.S. General Accounting Office, "National Missile Defense: Risk and Funding Implications for the Space-Based Infrared Low Component," GAO/NSIAD-97-16, (Washington D.C., U.S. General Accounting Office, 1997), pages 16-23.
[5] See, for example, discussion between Lieutenant General Ronald T. Kadish, Director of the Ballistic Missile Defense Organization, and Senator Joseph Biden, U.S. Senate Committee on Foreign Relations, "The Administration's Missile Defense Program and the ABM Treaty," S.HRG 107-110, July 24th, 2001, (Washington D.C., U.S. Government Publications Office, 2001), pages 26-27.

the ABM Treaty; the Bush Administration announced in December 2001 that it would abandon the treaty as of June 2002.[6]

Probabilistic Analysis

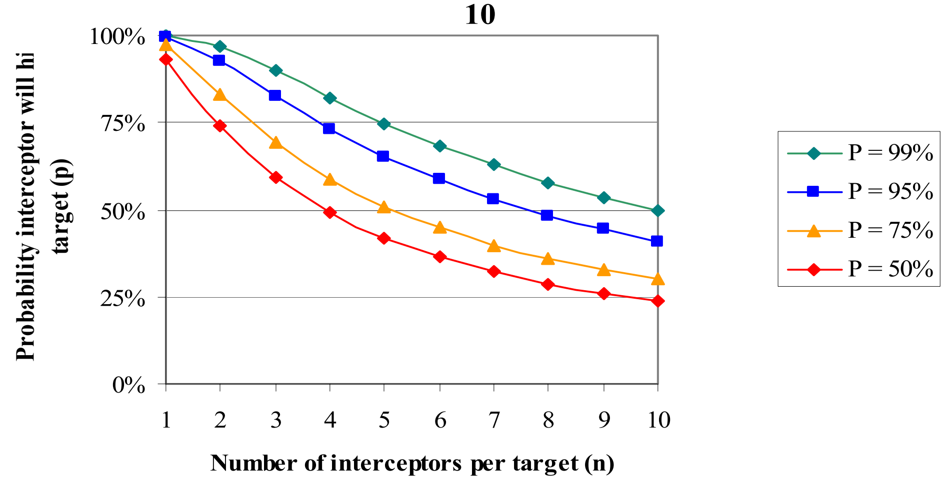
Given some simplifying assumptions, the likelihood that a defense will destroy all targets (a "leak-proof" defense) can be represented by the following equation:[7]

$P = (1-(1-p)^n)^N$ where

P = Probability of leak-proof defense
p = Probability that interceptor will hit target[8]
n = Number of interceptors fired at each target
N = Number of targets

One can use this equation in order to explore how effective (represented by P) are different technologies (represented by varying p and n) facing varying attack sizes (represented by N). To the extent to which information is available, the goal of the system's designers is to build a defense that would be at least ninety-five percent effective against a limited number (on the order of ten) of unsophisticated missiles fired by states such as North Korea or Iran.[9]

Figure 1: Isoperformance Combinations of p and n: N = 10



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[6] White House Office of the Press Secretary, "REMARKS BY THE PRESIDENT ON NATIONAL MISSILE DEFENSE," December 13th, 2001. downloaded from http://www.fas.org/nuke/control/abmt/news/bushabm121301.htm.

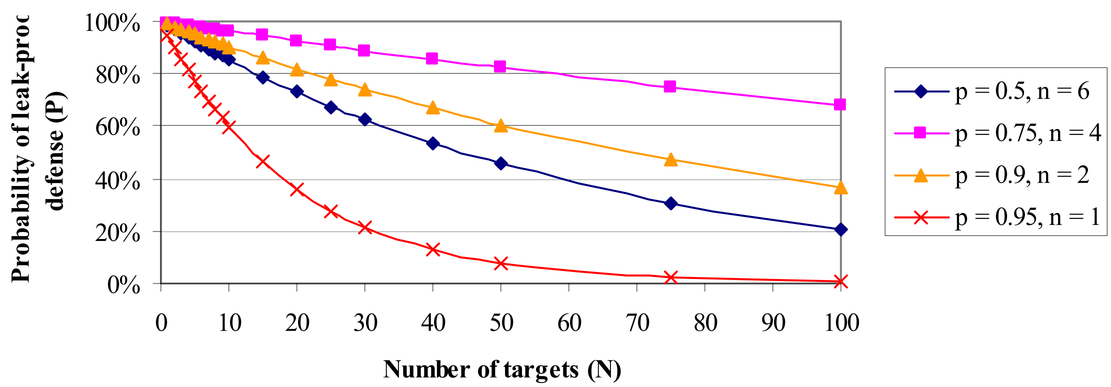
[7] Assumptions include interceptor independence and geographic irrelevance. Although leak-proof defense is only one of many possible performance metrics, it has considerable political weight; politicians would be hard-pressed to explain developing a system that would reduce the expected value of the number of cities destroyed as long as that expected value was greater than zero.

[8] UCS/MIT, Countermeasures, pages 94-102 for a discussion of the difference between p and the confidence one might have in the value of p.

[9] Michael Dornheim, "Missile Defense Design Juggles Complex Factors," *Aviation Week and Space Technology*, February 24th, 1997, 54-56, page 55.

Figure 1 shows the probability that different combinations of p and n would be able to defend against a ten-warhead attack with no countermeasures; the second line down shows combinations of p and n that would be required to meet the 95% goal. Figure 2 shows the effectiveness of several hypothetical defenses (combinations of p and n) against varying attack sizes. The figures suggest several points. First, unless the interceptor is exceptionally accurate (p > 95%), it will be necessary to design defenses to fire more than one interceptor at each target. Second, even if the size of an attack is on the order of ten targets, a defense still has a reasonable probability of being leak-proof. Defending against tens or hundreds of warheads, however, requires a large number of highly accurate interceptors, and appears infeasible given current technologies.

Figure 2: Probability of Leak-Proof Defense (P) for Hypothetical Combinations of p and n



For the purpose of this section and the analyses that follow, four limited attack scenarios were selected, reflecting a range of limited ballistic attacks that might be carried out by terrorists, small states such as North Korea, Iran, or Iraq (the "axis of evil"), or by large nuclear powers such as China or Russia.

- Very small, unsophisticated – two warheads, no countermeasures
- Small, unsophisticated – five warheads, no countermeasures
- Moderate, unsophisticated – ten warheads, no countermeasures
- Moderate, sophisticated – ten missiles, each carrying one warhead and three countermeasures

To counter these hypothetical attacks, it was assumed that the United States could deploy (in the next decade or so) five basic architectures: [10]

- Ground-based midcourse interceptors (100 missiles per base, destroying targets 50% of the time, with the ability to fire up to six at each incoming object)

[10] Probabilities and rates of fire are assumed. They are, at best, averages that encapsulate issues like geography, technical failures within individual components of the system, or of system integration.

- Sea-based midcourse interceptors (20 available missiles per ship, destroying targets 75% of the time, with the ability to fire up to four at each incoming object[11]
- Both the ground-based and sea-based midcourse interceptors could be coupled with SBIRS satellites that are assumed to distinguish accurately between warheads and decoys[12]
- Boost-phase interceptors, either ship-based or airborne (5 shots per platform, destroying targets 90% of the time, with the ability to fire up to twice at each missile). Decoy-distinguishing satellites would not add value to this system.

Given the set of attack scenarios, the defense assumptions, and the basic equation, one can calculate P values. Table 1 shows how the five different architectures might fare against attacks. A graphical presentation of the probabilities was chosen, rather than a numerical one. In keeping with the new homeland defense color system:

- Green = Better than 95% chance of leak-proof defense against attack
- Yellow = Between 75% and 95% chance
- Orange = Between 50% and 75% chance
- Red = Less than 50% chance

Table 1 – Attack and Defense Scenarios

Architecture	Very Small	Small	Moderate, unsophisticated	Moderate, sophisticated
C-1	Green	Yellow	Yellow	Red
C-2	Green	Yellow	Yellow	Yellow
Sea-1	Green	Green	Orange	Red
Sea-2	Green	Green	Orange	Orange
Air/sea Boost	Green	Orange	Red	Red

The table suggests that the five architectures are roughly equally able to defend against very small attacks, though there are significant differences as attacks grow larger. The ground-based system is less effective than others when attacks are small. At the same time, the ability to fire up to 100 interceptors means that this system is superior when attacks grow large. The sea-based mid-course interceptors are more likely to hit targets than their land-based counterparts; the system's performance, however, is constrained by the small number of available interceptors. Boost-phase defenses are assumed to have an

[11] The assumed difference between ship-based and ground-based missiles is that ground-based interceptors are intended to collide head-on with targets, while ship-based missiles could be used to hit missiles from the side or even behind. The lower closing velocity of ship-based interceptors gives them greater maneuverability and better target recognition. At the same time, fewer could be launched against any individual target because of timing constraints (and, depending upon the ship design, design constraints as well).

[12] If the system could distinguish, it would ignore decoys. If it could not, decoys were assumed to be identical to warheads and fired at accordingly. In Table 1, "C-1" refers to a ground-based midcourse system without SBIRS, and "C-2" to one with it; "Sea-1" refers to a sea-based midcourse system without SBIRS, while "Sea-2" refers to one with it.

intermediate capability to hit individual targets, and are also heavily constrained by their rate of fire.

The analysis suggests that there are definite performance trade-offs between sea-based and ground-based systems, and that even without warhead/decoy discrimination capability, both sea-based and ground-based systems can be effective by shooting at everything as long as there are on the order of ten total targets. Boost-phase systems, taken alone, have lower performance than their midcourse counterparts, and may therefore be more useful as components of a layered system than as a stand-alone defense.[13]

Implications

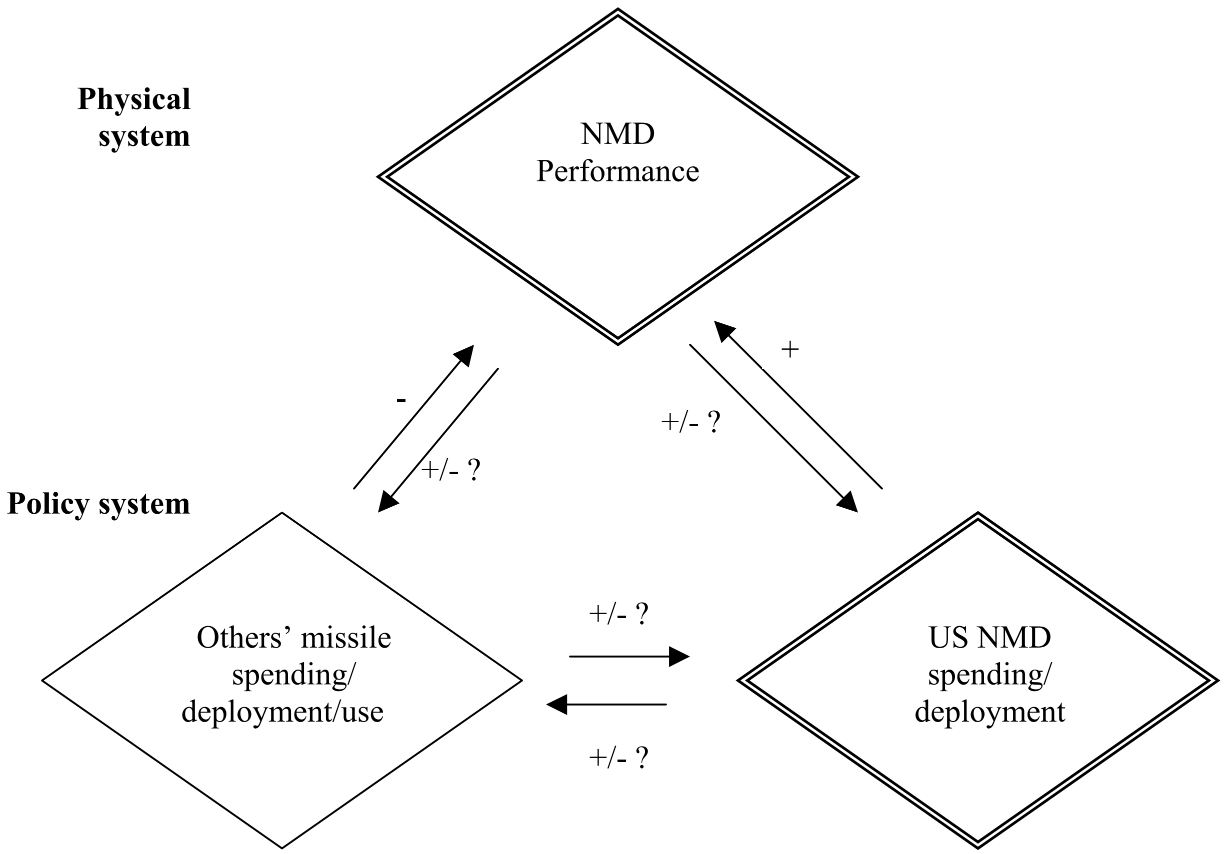
This analysis suggests that even a rudimentary probabilistic and scenario analysis provides considerable information to decision-makers about both the relative and absolute performance of missile defense systems. Although there is considerable uncertainty in the estimates, there appears to be sufficient information to suggest that missile defense architectures should be able to defend the United States against the type of very limited ballistic missile attack that a "rogue" state or terrorist group might attempt. At the same time, none of the first-generation systems would be effective against large, sophisticated attacks that Russia or even China might launch. Finally, the use of a qualitative representation of efficacy seems to be better attuned to how policy-makers might think about whether to purchase a missile defense system, or the implications of military scenarios that might require the system's use, than does a probabilistic estimate.

CLIOS Representation

This section of the paper presents a partial CLIOS representation of the missile defense problem.[14] Figure 3 shows the broad outline of the NMD system – the inter-relationship among the spending on missile defense by the United States, on missiles and warheads by others who may use them against the United States, and the performance of the NMD system. The figure shows that NMD is a very tightly coupled system. It also shows that some of these relationships are clear: greater spending on NMD will improve the performance of the system, while greater spending on missiles and countermeasures by opponents will degrade it. At the same time, other relationships are less certain. For example, will a missile defense system encourage opponents to spend more to develop weapons of mass destruction, or deter them and cause them to spend less?

[13] The system analysis below compares boost-midcourse combinations with midcourse-only and boost-only systems.
[14] CLIOS representation follows Joseph Sussman and Rebecca Dodder, "The Concept of a 'CLIOS' Analysis Illustrated by the Mexico City Case," Engineering Systems Division Symposium, May 2002. This section primarily performs steps 3-5 of the CLIOS process, while other sections of the paper perform several of the other steps. CLIOS is less quantitative than other systems approaches like system dynamics.

Figure 3 – Top-Level CLIOS Representation



Note: Text accompanying links indicates whether each link is likely to have a positive or negative influence. For four of the six links, there is uncertainty regarding the sign.

The idea of "arms races" – positive feedback in weapons purchases – has been a recurring theme in the history of nuclear weapons; Figure 3 suggests a mechanism through which an arms race could occur. Should existing missile states like Russia or China respond to deployment of NMD by the United States by increasing their own ballistic missile programs, it would both put pressure on the United States to further expand NMD and could lead the United States to maintain or increase the size of its ballistic missile arsenal. Another potential avenue for feedback would be for existing missile states to sell complex technologies to emerging missile states like Iran or Iraq. Proliferation of missile technologies could force the United States to purchase a more robust missile defense. At the same time, there are possibilities for negative feedback and greater stability. Building NMD could decrease the likelihood that in any given crisis missiles would be launched against the United States, as potential users would need to have greater confidence in success. Successful deterrence could lead both the United States and its adversaries to spend less on missiles, strengthening stability further. As Sussman and Dodder suggest, one way to gain further insight into the system is to expand the individual boxes of Figure 3.

Expanding the NMD Performance Box

One way of thinking about NMD as a system is to consider how information (communications between operators, detection of missiles, etc.) flows through it. As an example, Figure 4 shows how components of a ground-based NMD system are likely to inter-connect and communicate, as well as how the components contribute to evaluation of the system's performance.[15] The requirement that a large, distributed number of system elements correctly identify and respond to missile launches under extreme time pressure suggests that emergent behavior, as well as the failure of individual components or the overwhelming of the system by a massive number of targets, could degrade system performance. While the potential for emergence depends upon NMD's design, there appears to be three likely classes of emergent behavior that might degrade performance:

- Mistaken identification of launches
- Erroneous targeting
- Command confusion

Mistaken identity errors could take several forms. Mistaking a missile test or satellite launch for an attack against the United States could lead to the system destroying a target or targets that it should not have.[16] Such a type 2 error[17] might be a public relations nightmare for the NMD program, but American lives would not be lost as a result. In addition, it may be the easiest error to prevent. There are already protocols for notification when launching missiles or other space-bound objects; the responsibility should countries fail to adhere to these protocols in an NMD environment would be shared, if not falling squarely upon the launching nation.

A variation on the mistaken identity problem would be the inability to identify ballistic missile launches during an active conflict. Especially were the United States engaged with a country of modest size such as North Korea, sensors would be seeing a large number of potential attacks emanating from a limited geographic area; NMD sensors and operators would need to distinguish anti-aircraft missile launches, explosions, or even decoy launches from true threats. Mistakenly targeting false launches, or ignoring true ones, would be a larger problem for boost-phase systems than for midcourse designs;

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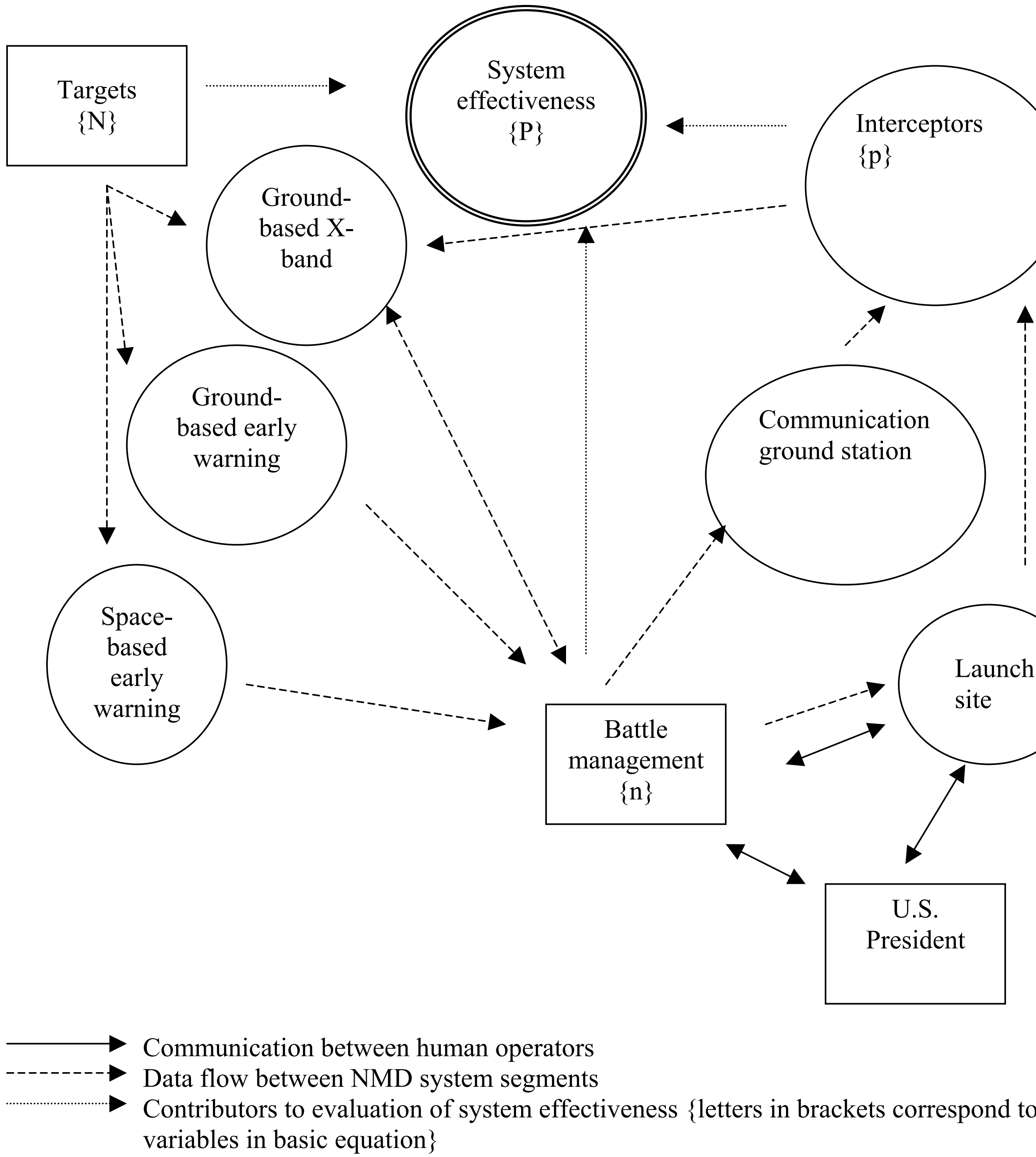
[15] Different NMD architectures would vary Figure 4 somewhat. Ship-based systems integrate communications with the interceptor and tracking into the launch platform; airborne lasers integrate early warning and tracking into the launch platform. Each architecture therefore contains slightly different possibilities for emergence.

[16] Russia nearly launched missiles in 1995, fearing a Norwegian scientific experiment was actually a nuclear missile. See Joseph Anselmo, "Russian Threat Still Massive," *Aviation Week and Space Technology,* February 24th, 1997, pages 48-49, page 49; Geoffrey Forden relates another story of mistaken identity, from the early days of the Soviet space-based tracking network. Geoffrey Forden, "Russia's Early Warning System: Which Came First, Technology or Doctrine?" *Breakthroughs* 10(1) Spring 2001, 11-20, 14-15. The United States has also had its share of false alarms. See "Report of Senate Gary Hart and Senator Barry Goldwater to the Committee on Armed Services, U.S. Senate," Senate Report 80 S202-5, October 9th, 1980 (Washington D.C., U.S. GPO, 1980), 4-5.

[17] Type 1 error = false negative; type 2 error = false positive

boost-phase designs operate under greater time pressure and rely on fewer independent sensors.

Figure 4 – NMD Performance Expanded – Midcourse Ground-based Interceptor Architecture



A second type of emergent behavior is for subtle errors in the computer software underlying the system to cause the system to function "correctly" but fail to intercept targets. An example would be for the interceptor's onboard sensors to identify debris or decoys (rather than warheads) as the real targets. This possibility is more significant for midcourse systems than for boost-phase designs. Critics of NMD development have argued that the discrimination problem is the Achilles heel of midcourse systems. The basic equation assumes that the probability that an interceptor will hit its target is independent of the number of targets, but one would imagine that the likelihood of incorrect targeting increases with the number of targets.[18] Depending upon the final design of the battle management system, errors caused by mistaken targeting stemming from "correct" system operation might significantly affect system performance.

A final concern is that even were the sensors and battle management systems to function perfectly, the humans who decide whether or not to fire might misinterpret data or react too slowly for the system to be effective. For example, an attack "from the blue" of one or two missiles, launched at a time when worldwide tensions were relatively low, could potentially confuse operators. The infra-red sensors and early-warning radars are very sensitive devices, and must correctly distinguish infrequent missile launches from other heat sources and radar returns. The history of early-warning systems includes examples of mistaken warnings of missile attacks; human operators provide an additional level of judgment to prevent type 2 errors. At the same time, the level of discrimination and redundant operating procedures required for error prevention creates the possibility that a cleverly designed attack would fool the system, slowing reaction time to the point where defenses could not be successfully brought to bear.[19]

Implications

Scrutinizing the NMD design for potential emergent behavior shows an example of nested complexity in the NMD system. Arms races may contribute to a decline in performance of a missile defense over and above the multiplication of potential targets because they increase the likelihood of NMD emergent behavior taking the form of mistaken identity or erroneous targeting. Such behavior undermines the assumptions underlying the basic equation, and suggests that the equation overestimates the likelihood of leak-proof defense as attacks grow large. One way to counter these emergent

[18] See UCS/MIT, Countermeasures Chapter 10. The authors argue that considerable testing of the system would increase confidence in its ability to handle large numbers of targets and varying types of decoys, but the current testing program is considerably more limited.

[19] The analogy here is to the September 11th bombings. The air traffic control system detected hijackings of several planes, but no one believed that they would be used to crash into buildings. Even after the first plane crashed into the World Trade Center (a clear indication that an attack was underway), there was insufficient time for defenses to respond to prevent the second WTC and Pentagon attacks. Given that a five-minute delay renders boost-phase defenses impotent, and a delay of fifteen to twenty minutes might circumvent a mid-course defense, a blue-sky attack does pose a concern. Circumstances that might contribute to the success of a blue-sky attack include attacking from unexpected locations (ship-based missiles or terrorists launching from countries without known missile programs) or launching just after new sensors become operational (while operators are learning to distinguish signals from noise). This concern was the focus of an organizational analysis that could not be included in the final version of this paper due to space constraints.

behaviors is to develop a layered defense based on multiple technologies. A layered design, as compared with a system built around a single technology, limits the influence of any particular emergent behavior.

Without precise understanding of how potential opponents might react to an NMD system, the systems perspective is excellent at highlighting the potential for feedback and for working through the consequences of choice but is less able to project what those choices are likely to be. A broad conclusion that may be drawn from the CLIOS analysis is that NMD decreases the likelihood of small, unsophisticated attacks against the United States, but increases the likelihood of more complex ones. While the probability distribution of successful missile attacks against the United States is unknowable, it would not be surprising if NMD decreased the mean (first moment) of that distribution while increasing its skew (third moment).

Game Theory

Game theory provides an alternative approach to representing inter-dependent decisions such as those that are involved in missile defense. Consider two games, shown as Figures 5 and 6. The first represents whether the United States should develop a missile defense in order to protect against missile launches against rogue states or terrorist groups. The second represents how the outcome of the first game might be viewed by China, and the decisions that the Chinese government might make based upon the United States' approach to missile defense.[20]

The Rogue State Game

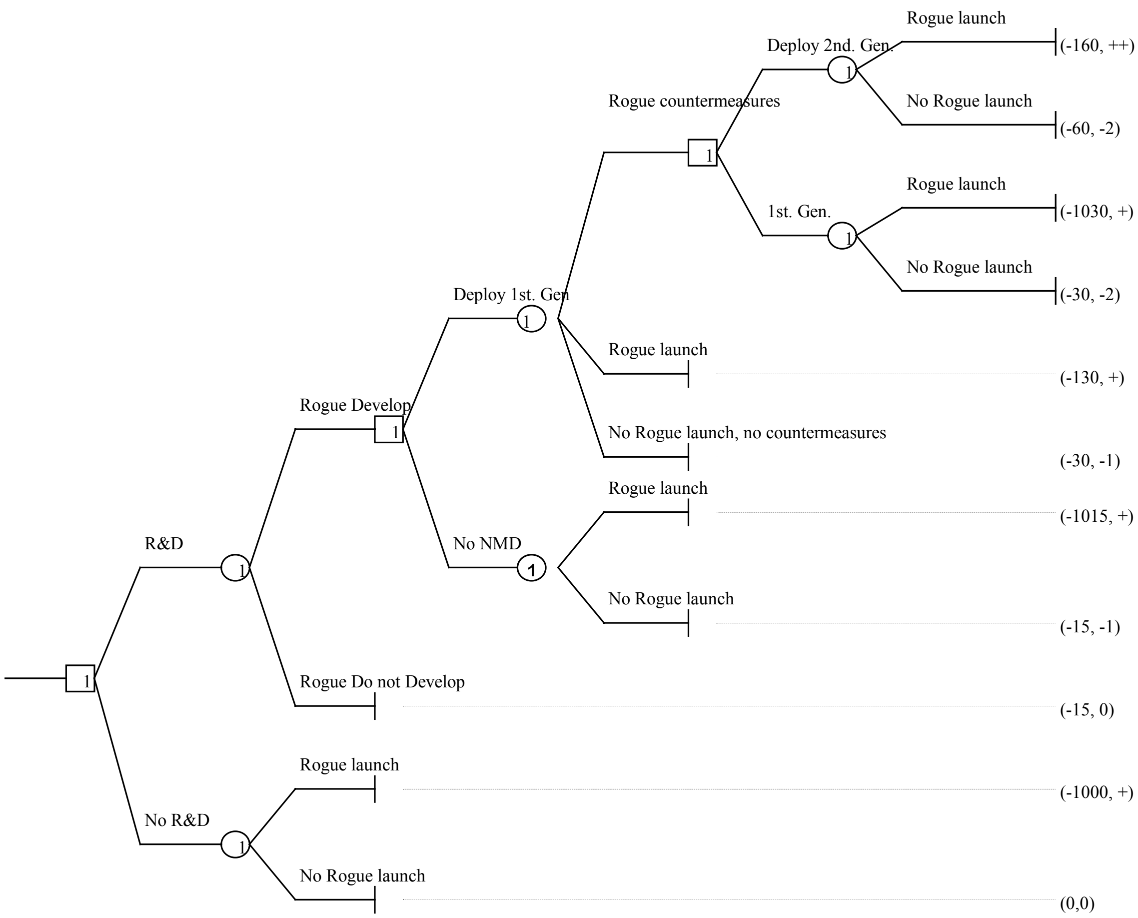
This game assumes that potential adversaries of the United States are several years away from developing the capability to launch ballistic missile attacks with nuclear warheads, and that therefore the United States could develop defenses at least as rapidly as rogues could develop missiles. The result of the game depends upon a key unknown – whether the leaders of rogue states would choose to launch missiles at the United States, knowing that retaliation would be severe. U.S. deterrence worked during the Gulf War, but the characterization of these states as "rogues" or members of an "axis of evil" suggests that the United States believes that their leaders might be willing to attack America in some circumstances despite the likelihood of massive retaliation. Given that assumption, the game suggests several points:

- In the absence of defenses, some rogues might attack the United States with ballistic missiles and nuclear weapons.
- American R&D (which signals our intent to develop NMD if necessary) would not deter rogues from pursuing their own missile/nuclear weapons programs.

[20] It is assumed that Russia, which maintains a considerable nuclear capability and has developed sophisticated missile defense countermeasures, would be able to defeat a limited system regardless of its design, and was therefore not included in either game. See Countermeasures, pages 5-9.

- Missile defenses, therefore, would be necessary to guard against this contingency.[21]

Figure 5 – Rogue State Game



Notes:

In reading the games, remember that the numbers are speculative, although the choices are real.

Boxes = U.S. decisions; circles = rogues' decisions
Numbers in boxes/circles: branch of tree chosen (1 = top, etc.)
Parentheses denote value of each branch, using format (U.S., rogue)
Value assumptions for U.S.: Cost of R&D = $15 billion; cost of 1st generation system = $30 billion; cost of 2nd generation system = $60 billion; cost if missile hits U.S. = $1000 billion. Probability that 1st generation system defends against simple attack or 2nd generation defends against complex attack = 90%

Value assumptions for rogues: Cost of developing nuclear weapon = $1 billion; cost of developing nuclear weapons and countermeasures = $2 billion; value of attacking United States even if United States responds = positive; value increases if attack is complex.

[21] Alternatively, the United States could pre-emptively destroy rogue states' ballistic missile/nuclear weapons programs.

A second key unknown, however, is whether the equilibrium between offense and defense would be stable. Critics of NMD have argued that even rogue states might be able to overwhelm limited defenses by developing relatively sophisticated yet inexpensive countermeasures.[22] The topmost branch of the game tree shows this possibility. The possibility of countermeasures suggests that the United States may be forced to develop ever more sophisticated defensive systems to counter relatively inexpensive threats, with the overall outcome of the game unclear.[23]

The China Game

The China game depends upon the recognition of the relationship between first-strike and second-strike capabilities. A missile defense capable of defending the United States against rogue states also gives the U.S. the freedom to use a small fraction of its own nuclear weapons against China's nuclear forces. The United States could rely upon missile defenses to stop the small fraction of Chinese missiles that survived a first strike and still threaten China with nuclear devastation. This game suggests several points:

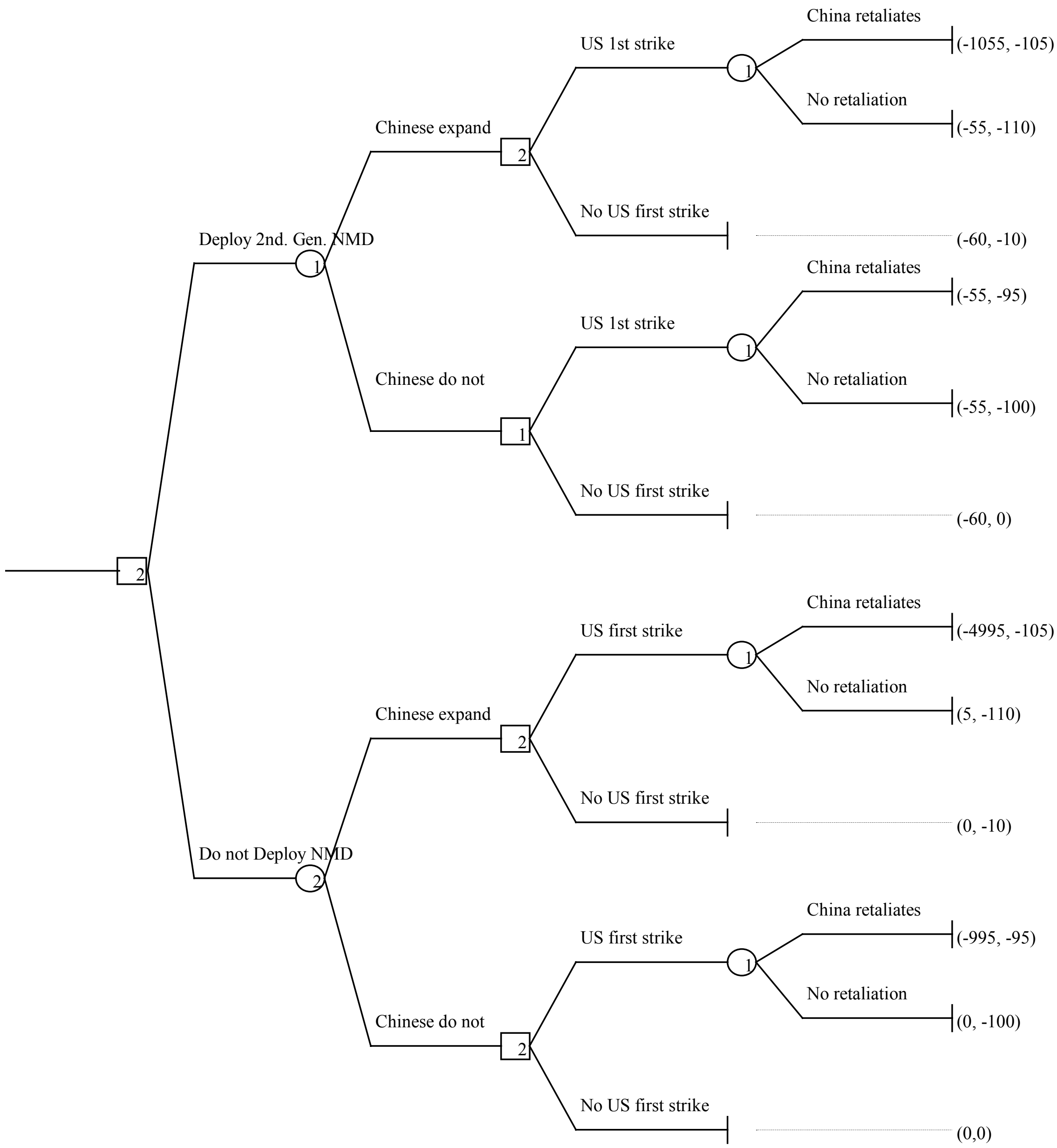
- Were the United States not worried about rogues, the rational decision would be not to develop missile defenses, in which case China would not expand its missile force.
- Combining the two games (figure not shown), however, suggests that the United States should build a missile defense, which leads to an arms race.
- The common expansion would return the two countries to roughly the same state of vulnerability, but would now give China greater capability to strike other nations than it now has.
- The rest of the world might consider the overall shift in weapons procurement stemming from a U.S. decision to deploy NMD as increasing risks rather than decreasing them. The most likely spill-over would be continuing development of nuclear technologies by India and Pakistan. [24]

[22] See, for example, UCS/MIT, Countermeasures, pages xx-xxi and 39-48.

[23] Moreover, this game covers only missile technologies. The game suggests that by pursuing missile defenses, the United States may lead rogue states to spend a larger fraction of their defense budgets on ballistic missile technology and less on other forces. Whether such a choice would make U.S. friends and allies more secure also is not clear.

[24] As a result, large investments by a coalition of nuclear states in preventing rogues from developing missiles and weapons of mass destruction improve the game outcome for all of them. Alternatively, the other nuclear powers could try to convince the United States that it misunderstands the psychology of the "rogue" states, and that they, too, are deterred by the threat of nuclear retaliation. Successful change in our perception would also prevent the arms race. But the no-NMD equilibrium is highly unstable.

Figure 6 – China Game



Notes:
Boxes = U.S. decisions; circles = China's decisions
Numbers in boxes/circles: branch of tree chosen (1 = top, etc.)
Parentheses denote value of each branch, using format (U.S., China)
Value assumptions for U.S.: cost of 2nd generation system = \$60 billion; cost if one missile hits U.S. = \$1000 billion; cost if ten missiles hit U.S. = \$5000 billion; political benefit of first strike = \$5 billion; probability that 2nd generation defends against ten missiles = 90%; probability that 2nd generation defends against one missile = 100%.

Value assumptions for China: Cost of expanding nuclear weapons = \$10 billion; cost if U.S. first strike hits China = \$100 billion; political benefit of responding to U.S. first strike = \$5.

Implications

Game theory is different from systems approaches like CLIOS or system dynamics in its explicit representation of choice, and its associated solution algorithm of looking forward and reasoning backward. CLIOS and system dynamics, on the other hand, are better able to represent feedback loops and complex behavior (as they represents behavior as a series of flows), but rely on simulation and sensitivity analysis to determine where equilibria lie. The game theory approach is better than CLIOS at focusing on specific aspects of a broad problem, but that advantage diminishes as games become more complex. While the individual rogue and China games are easy to analyze, incorporating third countries' decisions or broad trade-offs between the risks associated with ballistic missiles and more conventional weapons lead to games just as complicated as CLIOS representations.

A second implication of this approach is that it assumes that all players adopt the same decision-making framework – economic maximizers who look forward and reason backward. The rogue state game, especially, suggests that actors on the world stage do not necessarily think in this fashion. First, decision rules may not be based on conventional conceptions of utility maximization. Second and more generally, policy-makers with very short time horizons may not look all the way forward to the end of a game, leading to sub-optimal strategic choices and outcomes.

Systems Analysis

This section couples estimates of hypothetical NMD systems' performance with estimates of cost. This systems analysis performs several functions:

- Ruling out inefficient or dominated approaches
- Focusing on the trade-offs between comparable approaches, and
- Suggesting potential expansion paths for a system

Table 2 describes the potential NMD architectures that were included in the system analysis.[25] The system analysis combined cost data from Table 2 with effectiveness estimates calculated using the missile defense equation. It also included combinations of architectures (boost-phase and midcourse; ground-based midcourse and sea-based midcourse) as well as analyzing individual systems. Table 3 shows a simplified version of the analysis results. It removes those potential architectures that are dominated by

[25] The Congressional Budget Office estimated the cost of several in a 2002 report, and it is possible to extrapolate the costs of similar systems using the CBO data to estimate the marginal cost of additional ships or missiles. See Congressional Budget Office, "Letter to the Honorable Tom Daschle", January 31st, 2002, and Congressional Budget Office, "BUDGETARY AND TECHNICAL IMPLICATIONS OF THE ADMINISTRATION'S PLAN FOR NATIONAL MISSILE DEFENSE," April 2000. CBO has not estimated the costs of boost-phase defenses; for simplicity, the cost of a ship-based boost-phase defense was assumed to be comparable to that of a ship-based midcourse system. The ABL estimates were derived from General Accounting Office, GAO/NSIAD-98-37. While the estimated costs shown here are higher than Defense Department estimates, note that official estimates have often underestimated costs. See for example Stanley Kandebo, "U.S. Pursues NMD System to Prepare for 'Rogue' Threat," *Aviation Week and Space Technology* March 3rd, 1997, 44-45.

other systems offering similar or better performance at lower cost. Table 3 suggests several points:

- The Clinton Administration approach to missile defense looks relatively cost-effective when compared with the Bush Administration approach.
- Ship-based mid-course missile defense and ABL approaches appear to be worth researching, despite their relatively high cost. Their greatest utility lies in that they provide an alternative to developing space-based tracking sensors, which have already fallen behind schedule.[26] Combining ground-based midcourse systems with either ship-based midcourse systems or ABL would provide nearly equivalent performance to the full-fledged C-3 ground-based system at similar cost, and better performance than the C-2 system at 10-20% higher cost.[27]

Table 2 – Potential System Designs and Costs

Architecture	Interceptors	SBIRS Tracking Satellites?	Cost to 2015 (2001 B$)	Earliest Deployment Date
Threshold	20 ground-based missiles at 1 site	No	21.0	2005
C-1	100 ground-based missiles at 1 site	No	23.5	2007
C-2	100 ground-based missiles at 1 site	Yes	45.3	2009
C-3	250 ground-based missiles at 2 sites	Yes	55.5	2010
Sea-1	8 ships carrying midcourse missiles	No	34.8	2010
Sea-2	8 ships carrying midcourse missiles	Yes	48.8	2010
Sea-3	16 ships carrying midcourse missiles	No	48.1	2015
Sea-4	8 ships carrying boost-phase missiles	No	34.8	2010
Sea-5	16 ships carrying boost-phase missiles	No	48.1	2015
ABL-1	7 planes carrying lasers that destroy boosting missiles	No	25.0	2010
ABL-2	14 planes carrying lasers	No	38.8	2015
Space-based	Lasers/kill vehicles in orbit	No	63.0	2020

Table 3 suggests a cost-effective research and procurement path. In the short term, the Bush Administration should decide to purchase a limited ground-based system. While limited ground-based defenses are being developed and built, the Administration should continue research into air-based and sea-based systems and satellite tracking technologies. If it becomes necessary to purchase missile defenses that can deal with more sophisticated attacks, the Administration should purchase the most cost-effective of planes, ships or satellites. Such a procurement plan would buy a first-generation system that would cost approximately $30 billion through 2015. Were the decision made to go ahead with a second-generation defense, the costs would roughly double.

[26] See GAO/NSIAD-97-16, "National Missile Defense: Risk and Funding Implications for the Space-Based Infrared Low Component"; also see Robert Wall and David Fulghum, "Military Budget Boost Yields Marginal Change," http://www.aviationnow.com/content/publication/awst/20020211/aw24.htm.

[27] At the same time, the combination of X-band radars and space-based sensors envisioned for the C-2 and C-3 systems could be necessary were the threat more complicated.

Table 3 – Dominant Systems, Costs, and Effectiveness[28]

Architecture	Cost to 2015 (2001 B$)	Earliest Deployment Date	Effectiveness Against Attack Size: Very Small	Small	Moderate, unsophisticated	Moderate, sophisticated
Threshold	21.0	2005	Green	Orange	Red	Red
C-1	23.5	2007	Green	Yellow	Yellow	Red
Sea-1	34.8	2010	Green	Green	Orange	Red
C-2	45.3	2009	Green	Yellow	Yellow	Yellow
C-1 + ABL-1	48.5	2010	Green	Green	Yellow	Orange
Threshold + Sea-1	51.8	2010	Green	Green	Green	Orange
C-1 + Sea-1	54.3	2010	Green	Green	Green	Yellow
C-3	55.5	2010	Green	Green	Green	Green

At the same time, this conclusion depends on historical accident – the Clinton Administration's decision to research ground-based defenses to a greater extent than other approaches. Sunk costs make ground-based defenses appear to be less expensive than their counterparts, thereby improving cost-effectiveness trade-offs. The Clinton Administration spent approximately $6 billion on research into the ground-based segment of NMD between FY 1997 and FY 2001, as opposed to just under $2 billion for sea-based and $1 billion for airborne lasers.[29] Had the Clinton Administration not built its architecture around ABM compliance, the cost-effective expansion path might have looked different.

Implications

Compared with the other engineering tools, this one is most narrowly focused. Unlike either the systems or game theory approaches, it assumes that missile defense is a worthwhile objective, and discovers which architectures are likely to be cost-effective. Like game theory, system analysis assumes rationality as a goal of policy-making, as well

[28] System costs for layered missile-based systems were assumed to cost $4 billion less than the sum of individual costs (half of sea-based system R&D) because of savings from shared research. No overlap was assumed between ABL and missile-based systems.

[29] Statement of Lieutenant General Lester L. Lyles, USAF Director, Ballistic Missile Defense Organization before the Senate Defense Appropriations Subcommittee, April 22, 1998, http://www.acq.osd.mil/bmdo/bmdolink/pdf/70918b.pdf; Statement of Lieutenant General Lester L. Lyles, USAF Director, Ballistic Missile Defense Organization before the House Defense Appropriations Subcommittee, March 24th, 1999, http://www.acq.osd.mil/bmdo/bmdolink/html/lyle24mar99.html; Statement of Lieutenant General Ronald T. Kadish, USAF Director, Ballistic Missile Defense Organization before the Senate Defense Appropriations Subcommittee, April 12, 2000, http://www.acq.osd.mil/bmdo/bmdolink/html/kadish12apr00.html; BMDO Press Release, FY 01 President's Budget, February 4th, 2000, http://www.acq.osd.mil/bmdo/bmdolink/pdf/bmdopress.pdf; Department of Defense, Office of the Under Secretary of Defense (Comptroller), RDT&E Programs (R-1), FY 2001, February 2000, http://www.dtic.mil/comptroller/fy2001budget/fy2001r1.pdf; Department of Defense, Office of the Under Secretary of Defense (Comptroller), RDT&E Programs (R-1), FY 99, February 1998, http://www.dtic.mil/comptroller/fy1999budget/r1unclas.pdf

as the approach to it. It is easy to observe from the history of research into NMD that micro-economic rationality has not been a strong influence on decision-making. From a technology development standpoint, it would have been best to begin researching a wide variety of technologies and then choose the most cost-effective among them for deployment. The Clinton and second Bush Administrations have reversed the approach – Clinton choosing to define the architecture and technology narrowly, with Bush choosing to re-open the competition among systems just as one had emerged as an effective design. This is just one facet of the differences between the politics of weapons procurement and the projections of traditional decision theory and engineering analyses, as will be explored in the next section.

Political Analysis

The politics of weapon system development suggests a very different evolution for NMD than do the more traditional engineering systems analyses. Before projecting the future of missile defense, it is useful to touch briefly on how the United States purchases weapons, and on broad political trends surrounding the defense budget in general and missile defense in particular.

General Trends

At the end of the Cold War, observers expected the U.S. defense budget to shrink rapidly to match the declining threat from the Soviet Union. Yet during the 1990s, the defense budget remained at nearly ninety percent of Cold War levels. One reason for the continued high level of spending was that military planners successfully argued that a large force was necessary for the United States to deal with two regional wars such as Desert Storm simultaneously. At the same time, Congress, the armed services, and the Defense Department chose to budget in a fashion that minimized political conflicts but increased the cost of defense.[30]

One hallmark of 1990s weapons procurement has been the continuation of projects with strong political support but limited military rationale. Congress has resisted the closing of bases and production lines, resulting in purchases of weapons for which the services have not asked and maintaining a duplicative and inefficient infrastructure.[31] Each service retains roughly the same percentage of the military budget as it did during the Cold War, despite the change in threats and likely deployments. Cost savings came from across-the-board reductions of personnel and military formations rather than from radical re-orientations. Similarly, the services have chosen to purchase fewer units of new weapons rather than completely eliminate entire systems.[32] Even though the military talked during the 1990s about a "revolution in military affairs" that would radically

[30] Cindy Williams, ed., *Holding the Line*, (Cambridge, MIT Press, 2001): chapter 2, 40-45.
[31] Sapolsky, "Buying Weapons Without an Enemy," *Breakthroughs* 10(1), Spring 2001, 34-44, 36-38; Holding the Line, chapter 3.
[32] Holding the Line, chapter 2, 44-46.

transform the services, spending on revolutionary activities has been limited, representing an incremental increase in spending rather than a new blueprint for it.[33]

Looking at general political trends, strong public support for the war on terrorism not only gives politicians the incentive to support the increases in defense budgets that would allow the services to add new programs like missile defense without trading off existing ones, but also concerns over terrorism provide a rationale for missile defense – airplanes today, missiles tomorrow.[34] Defense may re-emerge as a partisan issue in the run-up to the 2004 election; Democratic control over the White House after 2004 may limit the move toward second-generation defenses.

At the same time, programs begun today lead to procurement decisions tomorrow. The Defense Department projects that spending will rise from $331 billion in fiscal year 2002 to $451 billion by fiscal year 2007, while procurement spending will rise from $61 billion in FY 2002 to $99 billion in FY 2007.[35] Current missile defense spending of roughly $8 billion already represents more than two percent of the defense budget, and nearly one-sixth of the defense R&D budget. Concerns over spending are likely to mount, however, as procurement intensifies; even the cost-effective spending proposal generated through systems analysis represents approximately ten percent of the total procurement budget between 2007 and 2010, and more than three percent of the total defense budget. This level of costs, while seemingly manageable, is approximately comparable to the cost of the Polaris missile submarine, probably the best example of an innovative, well-run, highly-successful weapons acquisition program. Even in the three years when Polaris R&D spending was highest, it represented no more than ten percent of the R&D budget, and Polaris exceeded three percent of the defense budget for only three years.[36]

The current plans of the Bush Administration, however, call for development of a layered defense that would encompass ship-based, airborne, and space-based defenses as well as ground-based interceptors; were all of the systems developed and then purchased, actual spending would be considerably higher than three percent of the defense budget.[37] Moreover, procurement of NMD will occur at the same time as when the services will be purchasing the next generation of ships and aircraft.[38] Especially should the economy fail to improve to the extent projected and deficits continue into the future, missile defenses

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[33] Holding the Line, chapter 1, 2-3; note that even the FY 2003 defense budget appears to follow the pattern of incremental change, albeit at a much higher funding level. See Cindy Williams, "The Bush Defense Budget: In With the Old in 2003," *Newsday,* February 3rd, 2002.
[34] Conversation with Cindy Williams, February 20th, 2002.
[35] U.S. Department of Defense, "Details Of Fiscal 2003 Department Of Defense (DoD) Budget Request," News Release 049-02, February 4th, 2002, http://www.defenselink.mil/news/Feb2002/b02042002_bt049-02.html. As a comparison, the Clinton Administration FY 2000 budget projected FY 2005 defense spending of $333 billion and FY 2007 spending of $357 billion. See Congressional Research Service, "Appropriations for 2000: Defense," CRS Report RL30205, July 1999, http://www.senate.gov/~dpc/crs/reports/00_approps/RL30205.pdf, Tables 2, 4.
[36] Harvey Sapolsky, *The Polaris System Development*, (Cambridge, Harvard University Press, 1972): vii. Calculations estimated from pages 166, 169, 172.
[37] Compare CRS Table 5 with DoD Details of Budget Request, Testimony of Lt. General Ronald Kadish before the House Armed Services Committee, February 27th, 2002.
[38] Conversation with Cindy Williams, February 20th, 2002.

are likely to be purchased in an atmosphere of budgetary stringency and intense competition for resources with other defense priorities.

Implications for Missile Defense as a System

The politics of weapons procurement and missile defense suggest several predictions for missile defense as a system.

- The large funding increases for missile defense in the FY 2002 and 2003 budgets will lead to the development and eventual procurement of airborne and sea-based missile defenses, in addition to ground-based interceptors. The pressure for procurement will stem from three sources.
    - Because of the war on terrorism, Congressional oversight of the defense budget after September 11th is likely to be weaker until war ends, giving the Defense Department more autonomy to speed research and development.[39]
    - Once components have been developed, there will be pressure from Congress and contractors to purchase them (the "camel's nose under the tent").
    - The armed services are likely to prefer flexible systems such as airborne lasers and AEGIS ships that both function as national missile defenses and meet the services' other mission requirements to dedicated national missile defense components such as ground-based interceptors.[40]
- The addition of components to the missile defense architecture will complicate the task of system integration and cause cost increases.
- At the same time, budgetary pressures at the end of the decade will limit spending for NMD system components.
    - Congress will buy fewer pieces of each interceptor system or radar/satellite system than the architecture requires.
    - Testing programs will be limited, and realistic testing highly unlikely.
    - NMD, despite being a high priority of the current Secretary of Defense, will not be able to generate the reputation for excellence that can protect high-profile projects from scrutiny and budget cuts.[41]
- All this being said, the United States probably will field a limited defense against ballistic missiles by the end of the decade.
    - It will probably be roughly as capable as the Clinton Administration C-1 architecture.
    - It will be more costly, and probably will take longer to build.

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[39] Conversation with Robert Dare, February 6th, 2002.

[40] Conversation with Robert Dare, February 6th, 2002.

[41] See Sapolsky, the Polaris System Development, chapter 8 for lessons for successfully managing weapons system development programs. NMD programs have already faced considerable scrutiny from Congressional support agencies like the General Accounting Office (for example NSIAD-97-16, NSIAD-98-37, NSIAD-98-153, NSIAD-00-121, NSIAD-00-131) and Congressional Budget Office. Moreover, the ideologically charged nature of missile defense has made it controversial in the past, and likely will continue to do so in the future.

- It will be more reliable in some ways (multiple interceptor technologies with less-dependent failure modes) but may also be less reliable in others (system integration, limited sensors).

Implications

Comparing the political analysis with the engineering-based analyses above highlights the differences between a “traditional” decision theory or economics approach and the more nuanced view that engineering systems provides. CLIOS and its cousins are in one sense the closest of the engineering tools to the political approach. Policy-makers at least implicitly carry systems diagrams such as the CLIOS representations shown in Figures 3-4 in their heads. Individual policy-makers focus on small parts of the system under their jurisdiction, and treat other pieces as constraints on their activities. At the same time, CLIOS (and other systems approaches to an even larger extent) imply that while the world is complex, it is also continuous. Choices by policy-makers – events such as September 11th or the switch of the Senate from Republican to Democratic control – are represented as changes in signs or quantities of parameters, hiding the human element.

Game theory’s assumption of value-maximizing rationality both ignores the way in which policy-makers choose and hides the most important questions for analysis. Few policy-makers, at least in the United States, have an interest in looking all the way forward to the end of a game before reasoning backward; given the tenure of elected officials, short-term maximization is a better description. Moreover, the key variable in the rogue state game is the value function of individuals such as Iraq’s Saddam Hussein or North Korea’s Kim Jong Il. By definition, such leaders are assumed not to be rational value-maximizers. Yet in the absence of a rationality assumption, it becomes impossible to project whether or under what circumstances they would use such weapons against the United States, making reasoning backward quite difficult.

The economic and technical calculus underlying system analysis assumes a politics-free decision-making process. If only analysts could represent the value of a program as a single goal (defending the United States against ballistic missiles) and compare performance against cost, they could make cost-effective choices. Yet in the case of missile defense several goals are at stake in addition to homeland defense – the health of defense contractors, inter-service rivalries, party politics, and public confidence in U.S. security. Given that these goals cannot be quantified to the extent that cost or even projected performance can, let alone mathematically traded off against each other, systems analysis cannot develop cost-effectiveness curves. Systems analysis therefore only provides a goal toward which policy-makers can strive, as long as they recognize how and why they will fall short.

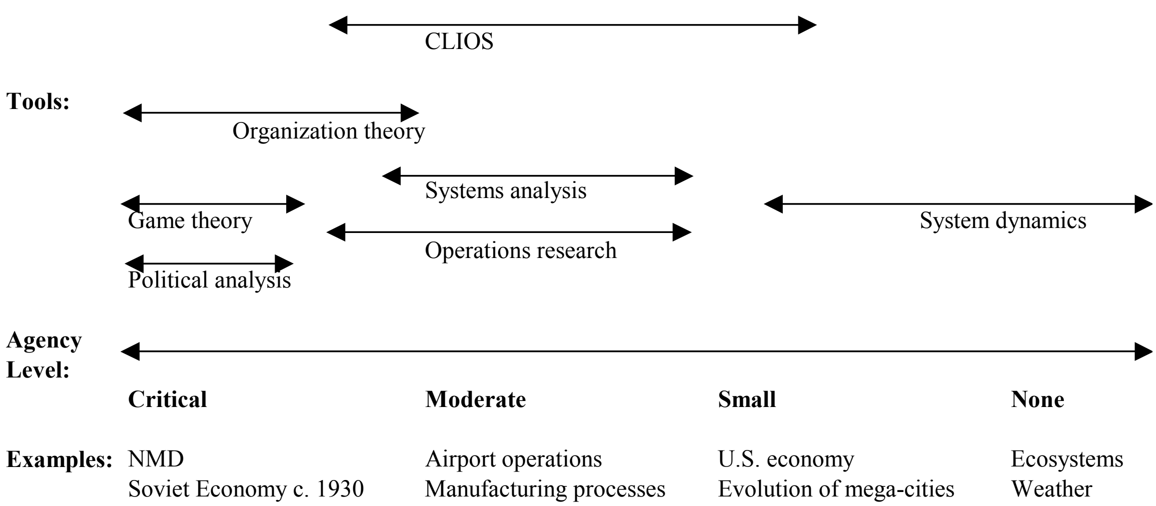
Conclusion: Engineering Systems Principles

This paper suggests two principles that should be incorporated into analyzing and especially teaching engineering systems:

- A taxonomy of tools
- The quantitative may be the enemy of the good

A taxonomy of tools. The analyses above show that applying multiple tools to the NMD problem yield different answers regarding how the system should be designed, how it is likely to perform, and the fundamental issues designers face. Figure 7, though speculative, offers one way of thinking about the question of tool selection that NMD illustrates. Agency – the extent to which individual human decisions about a system can perturb its trajectory – is one way of characterizing engineering systems problems and analytical tools. At one extreme, "natural" systems such as the solar system, weather, or undisturbed ecosystems, agency is absent. The evolution of these systems can be described (and if the equations are linear, accurately predicted) using differential equations and modeled using tools such as system dynamics. At the other extreme, individual decisions by policy-makers drive the system. To understand high-agency systems, political and organizational analysis is vital. Mathematical tools like game theory or systems analysis may help to structure choices or illuminate possibilities, but they will never be sufficient to predict the performance of, or even fully describe, the system.

Figure 7 -- Taxonomy of Tools Along Agency Axis



NMD represents an extreme case of divergence between the predictions of engineering systems tools, because of the importance of agency in this case. Missile defense is an issue over which Democrats and Republicans clash; changes in Congress or the presidency play a significant role in determining the shape of the program. Other world leaders may ignore or even actively counter any missile defense, and crises may reshape the perception of the missile threat, leading to a broad spectrum of potential responses that limits the insights of tools such as game theory or system dynamics. Finally, the very short time-frame in which defenses operate focuses attention on organizational questions.

Nevertheless, the applicability of the assertion that there is no single "best" tool applies to issues other than NMD. For example, the question of how a car company should run its factories or manage its global supply chain is the bread-and-butter of operations research. At the same time, the question of which car models and how many of each that company should build may be better understood using game theory or organizational analysis; operations research may help to bound choices and identify likely outcomes, but decision-makers are unlikely to rely solely upon them. Thinking through the extent to which human agency plays a role in the problem at hand helps in choosing suitable analytical tools.

The quantitative may be the enemy of the good. A key role that engineering systems practitioners play is to act as interpreters between decision-makers, whose training is likely to be in fields such as law or economics, and technologists. A brilliantly conceived and executed engineering study that does not resonate with decision-makers may be a technical success, but is an engineering systems failure. Expression of complex ideas in non-technical language, with the help of simple visual aids, is (or at least should be) an engineering systems core skill.

This principle is important in the NMD example because the rhetoric used by politicians to promote missile defense creates high expectations for the program. To the extent to which analysis can play any role in the debate over the program, the greatest value in engineering systems analyses at this point in time is to illuminate, using ideas policy-makers can understand and relate to, the relationship between the goal of a leak-proof defense and likely actual performance. Whether or not the probability analysis developed as the first part of this paper is sufficient technically, qualitative representations of results such as those developed here may be crucial in educating non-technical policy-makers in the strengths, weaknesses, and trade-offs associated with pursuing missile defenses.

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