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THESIS

STRIKE IN DEFENSE: AN ANALYSIS OF USING STRIKE OPTIONS IN THEATER BALLISTIC MISSILE DEFENSE USING JOINT DEFENDER

by

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Theater ballistic missile defense is a crucial part of U.S. military strategy. Missile defense is a complex task that requires detailed planning. A tool to help planners construct theater ballistic missile defense plans provides the U.S. with a strategic advantage. Joint Defender (JDEF) is an optimization-based missile defense planning tool created by a research group at the Naval Postgraduate School in 2005. Given information about a potential attack and available defenders, JDEF provides an anticipated optimal attack and opposing defense plan for the best worst case for the opponents. Since its creation in 2005, its capabilities have been expanded to better combat modern missile warfare. Among other developments, JDEF now has the ability to strike a missile complex before launch. We demonstrate JDEF's use of strike-capable interceptors in two scenarios: a hypothetical small-scale attack from Iran and a large-scale attack from North Korea. JDEF returns an optimal defense plan for the small-scale Iran scenario that minimizes maximum expected damage by 97.2%. JDEF returns an optimal defense plan for the large-scale North Korea scenario that minimizes maximum expected damage by 89.3%. Both defense plans rely heavily on strike-capable interceptors.

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ABSTRACT

Theater ballistic missile defense is a crucial part of U.S. military strategy. Missile defense is a complex task that requires detailed planning. A tool to help planners construct theater ballistic missile defense plans provides the U.S. with a strategic advantage. Joint Defender (JDEF) is an optimization-based missile defense planning tool created by a research group at the Naval Postgraduate School in 2005. Given information about a potential attack and available defenders, JDEF provides an anticipated optimal attack and opposing defense plan for the best worst case for the opponents. Since its creation in 2005, its capabilities have been expanded to better combat modern missile warfare. Among other developments, JDEF now has the ability to strike a missile complex before launch. We demonstrate JDEF's use of strike-capable interceptors in two scenarios: a hypothetical small-scale attack from Iran and a large-scale attack from North Korea. JDEF returns an optimal defense plan for the small-scale Iran scenario that minimizes maximum expected damage by 97.2%. JDEF returns an optimal defense plan for the large-scale North Korea scenario that minimizes maximum expected damage by 89.3%. Both defense plans rely heavily on strike-capable interceptors.

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LIST OF ACRONYMS AND ABBREVIATIONS

AADC	Prototype Area Air Defense Commander System
ABM	anti-ballistic missile
AEGIS	Advanced Electronic Guided Interceptor System
C2	Command and Control
CG	U.S. Navy Cruiser
CPS	Conventional Prompt Strike
CSG	Carrier Strike Group
CVN	U.S. Navy Aircraft Carrier
CVW	Carrier Air Wing
DDG	U.S. Navy Destroyer
GMD	Ground-Based Midcourse Defense
ICBM	intercontinental ballistic missile
IRBM	intermediate range ballistic missile
ISR	intelligence, surveillance, and reconnaissance
JDEF	Joint Defender
MASC-F	Modeling and Simulation Contract-Framework Tools
MDA	Missile Defense Agency
MRBM	medium range ballistic missile
PAC-3	Patriot Advanced Capability 3
SRBM	short range ballistic missile
SSN	U.S. Navy Fast Attack submarine
TBMCS	Theater Battle Management Core System
TBMD	theater ballistic missile defense
THAAD	Terminal High Altitude Area Defense
TLAM	Tomahawk Land Attack Missile
V-2	first ballistic missile

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EXECUTIVE SUMMARY

Theater ballistic missile defense (TBMD) is a crucial part of U.S. military strategy. Many U.S. military platforms, including the U.S. Navy's surface combatants, are designed around missile defense. Our distributed maritime operations are oftentimes focused on ensuring we have missile defense systems within range of potential attacks. The U.S., therefore, has heavily invested in its missile defense systems. Despite the U.S.'s arsenal of anti-ballistic missile systems (ABM), TBMD is not as simple as detecting an attack and launching any ABM system. The defense planner must consider what missiles the attacker might launch from which launch sites at which targets in order to effectively plan where defenders should be positioned in order to engage these attacks. This is a complex problem for the planner.

The task of the planner becomes increasingly difficult as the scale of missile defense operations increases. Sending one carrier strike group (CSG) to address a potential threat might not be enough, depending on the size of a potential attack. However, sending multiple defense platforms to a specific area of the world is expensive and requires careful coordination. The planner must not only decide which platforms to send, but where to send them to ensure effective protection of defended assets at risk. Determining how well an asset is protected is difficult: just because a defender is located near an asset, it does not mean the asset is safe from attack. Manual planning leaves room for vulnerabilities that are unknown to the planner unless exposed by simulated (or actual) attack. Therefore, a tool to help the defense planner construct TBMD plans provides the U.S. with a strategic advantage by helping the planner save time, money, and resources.

Joint Defender (JDEF) was created by a research group at the Naval Postgraduate School in 2005 to suggest a counter-missile defense plan. JDEF is a two-sided optimization model for planning the pre-positioning of a set of defensive missile interdictors to counter a multiple-missile attack on a set of defended asset targets. It assumes prior knowledge of potential enemy launch sites, missiles, and their capabilities. Given a specific defended asset list with asset values, JDEF chooses among alternate positions for defending platforms, *assuming the enemy will sense radar emanations from and thus know these*

defensive positions before launching any attack, and decides which defensive weapons should engage which missile attacks with which interceptors. The problem is solved using a mixed integer linear optimization. It suggests optimal coordinates at which decision-makers should pre-position defender interceptors, and forecasts the attacker's best positioning and use of its missiles.

Since 2005, the evolution of ballistic missiles and missile defense has forced JDEF's creators to make changes. One major enhancement is the ability to model strike-capable interceptors that target missiles at the source of the launch as opposed to in flight. The aircraft carrier (CVN) and associated carrier air wing (CVW) provide the U.S. with a mobile strike capability that is advantageous in missile defense. Similarly, the U.S. has expanded its aircraft and submarine strike capabilities with the development of hypersonic strike missiles (which we refer to as conventional prompt strike (CPS) missiles) and the Tomahawk Land Attack Missile (TLAM).

Furthermore, JDEF now allows for the planner to take into consideration the use of SECRET defenders, such as a submarine used in a strike role. A SECRET defender is a platform that cannot be detected visually or by enemy radar. This provides a more realistic representation of U.S. missile defense capabilities. JDEF first optimizes the locations of SEEN defenders; once SEEN defenders have been assigned to their best locations, SECRET defenders are positioned to further minimize maximum expected damage.

Another important improvement is the ability for the planner to fix a defender in a specified position if desired. This is particularly useful for land-based platforms that might already be in specific locations, such as the AEGIS Ashore, Patriot, and THAAD. This is also useful for the CVW; the CVW will likely be tasked with missions other than striking missile complexes which might require it to be located somewhere specific.

JDEF also invites the planner to suggest positions it will evaluate in comparison to an optimal plan. This conveys to the planner a reassuring sense of control while at once offering an objective assessment of a suggested plan. (Intuitive manual plans are rarely competitive with the optimization—this problem is too complicated to evaluate in its entirety merely by hand.)

We demonstrate the capabilities of the modern version of JDEF using strike-capable platforms in scenarios of two different sizes. We first demonstrate how JDEF can be used to generate an optimal missile defense plan if Iran were to launch an attack against two assets: Tel Aviv, Israel and Warsaw, Poland. Given the suspected locations of Iranian launch sites, attacking missile types, ranges, and quantities, and defensive interceptor information, JDEF reports a two-sided optimal defense and strike plan. The output defense plan is the plan for the best-worst case scenario such that, if Iran were to launch the best possible attack against Tel Aviv and Warsaw, U.S. assets would be positioned to respond optimally.

Our second scenario demonstrates how JDEF can be applied to a potential situation in which North Korea launches an attack against four assets: Hiroshima, Japan; Yokosuka, Japan; Seoul, South Korea; and Guam Naval Base. Given information about North Korean launch sites, North Korean attacking missiles, and U.S. defensive interceptors and strike capabilities, JDEF generates an optimal defense plan to position U.S. platforms such that they can most effectively respond to a series of worst-case attacks against all four assets.

Data from both scenarios has been extracted from open sources. Launch-site locations and attacking missile ranges are estimates that provide a reasonable representation of both attacking countries' missile capabilities. Similarly, the defensive interceptor data used provide an estimate of the U.S.'s ballistic missile defense capabilities. Interceptors are broken down by interceptor type: strike, exo-atmospheric, and terminal. In its new ability to use strike as defensive measure, JDEF categorizes strike as an "interceptor." The interceptor type helps JDEF decide how an interceptor can be used in a defense plan. JDEF also requires that alternate candidate interceptor locations be input by the planner. These locations are broken down by interceptor type, and positions to which the interceptors can be feasibly moved to. All data can be adjusted by the planner to the desired classification level.

JDEF output from the North Korea scenario demonstrates how complex missile defense planning can be. This hairball diagram of an exchange is explained in Figure 1.

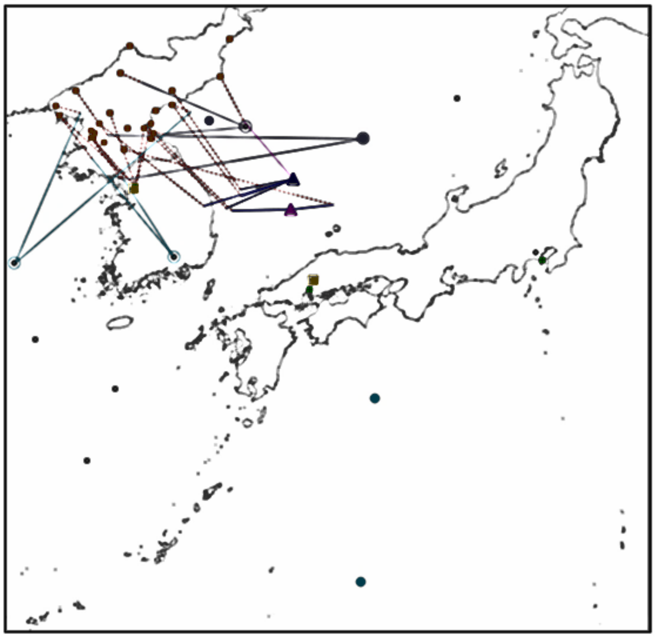

Figure 1. Output from the North Korea scenario to demonstrate complexity of missile defense planning.

In both scenarios, JDEF provides an adversary attack plan that reduces the maximum expected damage (the expected damage if the U.S. did not have any defenses) by at least 89%. Strike-capable platforms are shown to provide a strong advantage to the U.S. in missile defense. JDEF can be used to generate defense plans for scenarios of varying sizes. Because the planner provides candidate defender positions, all output positions are operationally valid and do not require adjustments. Overall, JDEF provides the U.S. with a strategic advantage in TBMD.

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I. INTRODUCTION

A. HISTORY OF THEATER BALLISTIC MISSILE DEFENSE

Ballistic missiles are initially powered and guided in ascent from launch and then continue on an arching trajectory outside the atmosphere, ultimately falling under gravity to a pre-determined target. Some can maneuver on descent. Since their creation in 1942, they have posed a significant threat. Counter-missile defense is at the forefront of military strategy and shapes the way the United States views and approaches conflict.

Powered missiles have been in development for centuries. In 1232 at the military siege of Kai-feng-fu, the Chinese used “fei huo tsian” (flying fire lances) against the Mongols. These missiles were merely unguided bottle rockets that exploded on impact with a target. Rocket and missile development continued over the next 700 years. The first true ballistic missile was the German V-2, which was developed during World War II (National Air and Space Agency 2021).

The German V-2 was first successfully launched in 1942 and marked a turning point in the war. It introduced a version of mass destruction that had not before been encountered. The V-2 was capable of flying 80 km above Earth over a maximum range of 350 km, and had an inertial guidance system that guided the missile to its target (Jane’s 2011). The V-2 descended noiselessly on its target and detonated on impact. Its stealth, range, and guidance technology instilled fear across the world as thousands of people died in V-2 attacks.

The V-2’s technology exploited serious national defense weaknesses. Once the V-2 was launched, there was no preventing it from reaching its target. Germany had built a weapon that was unstoppable. Therefore, unless the launch site was compromised, there was no way to defend against the V-2. This motivated the United States to start a new era of warfare, focused on developing and defending against ballistic missiles.

Ballistic missile defense is a key component of U.S. military strategy, and missile defense strategy has been continuously evolving since the invention of the first ballistic missile. Amidst concern that the Soviet Union was developing long range ballistic missiles to target the U.S., President Dwight Eisenhower commissioned missile defense programs to meet and ultimately surpass the Soviet Union's ballistic missile capabilities (Cirincione 2000). Through this program the Army developed Nike-Zeus, an anti-ballistic missile (ABM) system that was designed to intercept and destroy incoming ballistic missiles. Although not perfect, Nike-Zeus showed promise for future ABM technologies.

ABM technology development was controversial among world powers. In 1972, the United States and Soviet Union signed the ABM Treaty, which prevented either country from implementing ABM systems to defend territory nationwide (Lakoff and York 1989). It ultimately limited both countries to only land-based ABM technology, like the Nike-Zeus, which was not sufficient by itself to safeguard a nation. Nike-Zeus provided a layer of security that only slightly lessened the threat posed by Soviet missiles. The ABM Treaty was intended to prevent a defensive arms race that would undoubtedly foster the development of new offensive technologies. Neither country wanted to enter an arms race that had no foreseeable end.

Nike-Zeus was the first step in ABM, and it created a path forward for ABM technology. Since the creation of Nike-Zeus, the U.S. has developed three theater defense systems and one homeland defense system (Center for Arms Control and Non-Proliferation [CACNP] 2021). The homeland defense system, known as the Ground-Based Midcourse Defense (GMD) system, provides homeland protection from intercontinental ballistic missiles (ICBM).

Because the U.S. military emphasizes forward deterrence and practices forward deployment strategies, the U.S. maintains a strong ABM network overseas to protect U.S. allied assets (CACNP 2021). Theater ballistic missile defense (TBMD) systems are regional systems that target short-range ballistic missiles (SRBM, able to reach 1000 km), medium range ballistic missiles (MRBM, targeted between 1000 and 3000 km), and intermediate-range ballistic missiles (IRBM, targeted between 3000 and 5500 km range) (Missile Defense Agency 2020). TBMD technologies are both land-based and sea-based. Land-based TBMD technologies include the Patriot Advanced Capability (PAC-3) and the Terminal High Altitude Area Defense (THAAD) systems. The U.S.'s sea-based TBMD system is called the AEGIS, which can also be deployed on land with the AEGIS Ashore version. The U.S. continues to invest heavily in its ABM program in order to construct a broader range of ABM interceptors.

Ballistic missile defense allows the United States to maintain a base layer of protection from threats posed by nations possessing theater ballistic missiles. However, these ABM systems alone are not sufficient to guarantee full protection from any missile attack. Missile defense is not as simple as detecting an attack and pressing a button. A defense from an attack depends on the type of missile launched and location of the missile launched, among several other variables. Defender strike missiles or interceptors are limited in range and need to intercept an attack missile at a certain point in its trajectory in order to be effective. ABM systems, therefore, require U.S. military leaders to decide where to position them and how and when to employ them.

B. HISTORY OF JOINT DEFENDER AND DISCUSSION OF ALTERNATIVES

The U.S. has several TBMD pre-positioning planning tools. The Prototype Area Air Defense Commander (AADC) Capability was created by Prosser et. al. (2002) to provide the Area Air Defense Commander with a tool to plan and execute air defense plans in a timely manner. The AADC provides two capabilities: predictive theater air defense planning in a dynamic environment and continuous visualization of the battlespace to provide reliable situational awareness at all times. The AADC capability is one of the first tools created to help decision makers create missile defense plans tailored to specific scenarios.

The AADC’s planning and operations modules allow air defense commanders to plan, test, and analyze scenarios in a series of wargames. AADC monitors the theater in real-time and provides continuous updates on the battlespace; this allows air defense commanders to make informed decisions based on real-time data, not just previous information. AADC constructs an increasingly complex model as more factors are taken under consideration (Prosser et al. 2002). AADC then considers the number of air defense units, number of targets, number of threat areas (sorted by most to least threatened), attacking missile performance, and probability of kill of potential defended assets in order to generate an area of maneuver for each unit surrounding the positions of defending interceptors. This enumeration-based algorithm evaluates all unit placement possibilities in parallel, ultimately generating thousands (or more) of potential combinations. AADC does not take into consideration the enemy's strategy.

The Theater Battle Management Core System (TBMCS) is the U.S. Air Force's primary Command and Control (C2) system (Jane's 2022g). It is an integrated C2 and intelligence, surveillance, and reconnaissance (ISR) system that develops and distributes a force-level air battle plan. It allows for the planning and coordination of all theatre air operations, including missile defense strategy. TBMCS has threat and target evaluation abilities that provide mission planners with an automated tool for selecting which targets to engage with which aircraft or missile. It enables its planners to model actions of potential threats to assess the probability of nullification (i.e., successful interdiction) by a selected defensive interceptor. It does this by automating an overlay of potential launch fans, where the potential attacking missile tracks outbound from their launch point, with defensive interceptor envelopes. An interceptor envelope includes the area and altitude over which it is effective. However, TBMCS does not optimize a pre-positioning plan for defensive interceptors. Instead, it provides a plausible solution that tells decision-makers whether a specific plan will suggest that a selected defensive interceptor can intercept an attacking missile.

The Missile Defense Agency (MDA) relies on live launch tests to provide critical data demonstrating the readiness and effectiveness of the U.S.'s missile defense system. (Missile Defense Agency 2022). Modeling and Simulation Contract- Framework Tools (MASC-F) is a Lockheed Martin program that encompasses a variety of modeling and simulation techniques to help MDA evaluate missile defense strategy efficiency (Lockheed Martin 2019. The MASC-F program is still in development, and finalized models have not been published. The goal of MASC-F is to evaluate a variety of "what if" scenarios that evaluate system configurations and engagement conditions to determine if a given missile defense strategy is effective in defending assets. MASC-F is primarily intended to be used as an evaluation tool to be applied to an input scenario, and current Lockheed publications do not indicate that MASC-F will provide an optimal defense strategy. The MDA's call for a program like MASC-F demonstrates the need for more systems that provide decision-makers with effective missile defense plans.

Joint Defender (JDEF) was created by Brown et. al., 2005, to suggest a counter-missile defense plan. JDEF is a two-sided optimization model for planning the pre-positioning of a set of defensive missile interdictors to counter a multiple-missile attack on a set of defended asset targets. It assumes prior knowledge of potential enemy launch sites, missiles, and their capabilities. Given a specific defended asset list with asset values, JDEF chooses among alternate positions for defending platforms, *assuming the enemy will sense radar emanations from and thus know these defensive positions before launching any attack*, and decides which defensive weapons should engage which missile attacks with which interceptors. The problem is solved using a mixed integer linear optimization. It outputs optimal coordinates at which decision-makers should pre-position defender interceptors, as well as the attacker's anticipated best positioning and use of its missiles.

C. PURPOSE OF RESEARCH

JDEF has had to evolve over the past 20 years to incorporate new technological advancements, in particular from long-range radar launch detection and new interception and attacker launch site capabilities. One major enhancement is the use of cross-range, down-range intercept tables to estimate interceptor performance by determining the single-shot kill probability (called nullification probability in missile defense) of an interceptor fired at an attacking missile. Another major enhancement is the addition of strike-capable interdictors: instead of intercepting an attacking missile mid-course, these strike platforms hit the attacking missile launch-site or missile complex directly.

JDEF was first applied to a scenario in which North Korea (Democratic People's Republic of Korea) threatened an attack on U.S. allied defended assets. The U.S. had a set of counter-attack platforms to be pre-positioned to intercept these missile attacks. At the time of JDEF's creation, North Korea had only recently begun their missile proliferation program.

Since 2005, North Korea has heavily invested in its missile development program. Building a prolific missile program has been at the forefront of their military strategy for the past few decades. Consequently, the North Korea scenario applied in the first version of JDEF (in 2005) no longer provides a reliable picture, far underestimating the scope of their missile capabilities. A modernized North Korea scenario with current missile capabilities and current missile launch sites provides insight on how the United States can best counter threats posed by North Korea's missile program, perhaps with cooperation from its allies in the region who are now equipping themselves for missile defense.

Several other countries are rapidly developing their missile programs. Iran has created their ballistic missiles to provide a means to strike adversaries beyond their borders amidst the military sanctions imposed during the 1979 Islamic Revolution. Iran now has the ability to strike regional neighbors and Israeli and U.S. forces deployed in the region. China, North Korea, and Russia have been primary actors in aiding Iran's missile program development. A scenario illustrating Iran's missile capabilities applied to JDEF will provide insight on how the U.S. can plan to counter threats posed by Iran's growing missile program.

II. MODEL FORMULATION

The following is the model formulation of JDEF from Brown et. al., 2023. We use bold parameters and variables to refer to the entire vector of parameters or variables. We use italicized parameters and variables to refer to the single parameter or variable associated with particular indices.

A. THE ATTACKER

An optimization model expressing the Attacker's problem is AMAX($\widehat{\mathbf{Pnul}}$):

Indices and Index Sets

$m \in M$	attacking missile type
$s \in S$	Attacker launch site
$\{s\}_m$	set of sites that can launch missile type *m*
$t \in T$	target ("defended asset")
$a \in A$	attack launching a missile at a target
$a \in A_t \subseteq A$	attack *a* with target *t*
$\{s, m, n, t\}_a$	attack *a* is from site *s* with missile type *m* number *n* aimed at target *t*.

Data [units]

$epoch\_length$	planning horizon [time]
$\overline{fixed}_{s,m}$	Attacker's total supply of stationary type *m* missiles at launch site *s* [missiles]
$\overline{mobile}_m$	Attacker's total supply of mobile missile type *m* [missiles]
$\underline{move}_{s,m}, \overline{move}_{s,m}$	minimum and maximum number of mobile missile type *m* that Attacker can transport to launch site *s* [missiles]
$launch\_rate_{s,m}$	rate at which Attacker can prepare and launch missile type *m* from launch site *s* [missiles/time]

$\overline{attacks}_{s,m}$	maximum launches of missile type m from launch site s $\equiv \left\lceil launch\_rate_{s,m} * epoch\_length \right\rceil$ [missiles]
$\overline{missiles}_t$	maximum number of missiles that can attack target t [missiles]
$value_t$	value of target t [value]
Pk_a	probability that attack a hits and destroys its target $t(a)$, if not interdicted, intercepted or blocked, i.e., probability of kill [fraction]
h_a	action taken to interdict attack a
$\widehat{Pnul}_h$	probability that attack a has been interdicted (i.e., “nullified”) by Defender interdiction action h [fraction]

Decision Variables [units]

$MOVE_{s,m}$	type m mobile missiles transported to launch site s [missiles]
$AVAIL_{s,m}$	total of stationary and mobile type m missiles available at launch site s [missiles]
$ATTACK_a$	1 if attack a is conducted, 0 otherwise [binary]

(ATTACK, the vector of attacks $ATTACK_a$, is an “attack plan”)

$$Z_{\max}(\widehat{\mathbf{Pnul}}) = \max_{\substack{\mathbf{MOVE},\\ \mathbf{AVAIL},\\ \mathbf{ATTACK}}} \sum_t value_t \sum_{a \in A_t} Pk_a \left(1 - \widehat{Pnul}_{h_a}\right) ATTACK_a \qquad [\text{A0}]$$

$$\begin{aligned}
s.t. \sum_s MOVE_{s,m} \quad & \le \overline{mobile}_m & \forall\, m \quad & (\alpha_m) & [\text{A1}] \\
-MOVE_{s,m} + AVAIL_{s,m} \quad & \le \overline{fixed}_{s,m} & \forall s,m \quad & (\beta_{s,m}) & [\text{A2}] \\
-AVAIL_{s,m} + \sum_{a,\{s,m,n,t\}_a} ATTACK_a \quad & \le 0 & \forall s,m \quad & (\gamma_{s,m}) & [\text{A3}] \\
\sum_{a,\{s,m,n,t\}_a} ATTACK_a \quad & \le \overline{missiles}_t & \forall t \quad & (\delta_t) & [\text{A4}] \\
MOVE_{s,m} \in \{\underline{move}_{s,m}, \ldots, \overline{move}_{s,m}\} \quad & & \forall s,m \quad & (-\underline{\pi}_{s,m}, \overline{\pi}_{s,m}) & [\text{A5}] \\
AVAIL_{s,m} \in \{0, \ldots, \overline{attacks}_{s,m}\} \quad & & \forall s,m \quad & (\rho_{s,m}) & [\text{A6}] \\
ATTACK_a \in \{0,1\} \quad & & \forall a \quad & (\theta_a) & [\text{A7}]
\end{aligned}$$

Discussion: The Attacker's objective [A0] is to maximize total expected target damage, assuming a cumulative effect for multiple attacks. Constraints [A1] limit the number of mobile missiles of each type that can be transported to launch sites. Constraints [A2] combine mobile and fixed missiles at each launch site, and Constraints [A3] limit the number of missiles that can be launched from each launch site. Constraints [A4] limit the number of missiles that can attack each target. Bounds [A5] limit the number of mobile missiles of each type that can be transported to each launch site, [A6] the maximum number of missiles that can be launched in some limited planning epoch, and [A7] stipulates binary launch decisions. The domain of constraints [A2], [A3], [A5] and [A6] is $m \times \{s\}_m$, simplified here to reduce notational clutter.

B. THE DEFENDER

New Indices and Index Sets [~cardinality in Iran scenario, ~cardinality in North Korea scenario]

$p \in P$	defending platform (ordinal set) [~11, ~18]
$c \in C$	defending platform classes [~8, ~8]
$c(p)$	class of platform p, $c(p) \in C$
$\{p\}_c$	set of platforms in class c
$group$	set of platforms that must remain collocated
$\{p\}_{group}$	set of platforms in collocated group
$g \in G$	candidate stationing positions for a defending platform (alias $g1, g2$)
$g \in G_c \subseteq G$	candidate stationing positions for a defending platform of class c
$i \in I$	defensive missile types [~3, ~3]
$d \in D$	defense options (e.g., number and types of missiles in salvo)

	(E.g., a standard Patriot salvo is of two interceptors fired seconds apart.) (alias $d1$, $d2$)
$v \in V$	Defense volley
$h \in H$	interdiction action that can include multiple defense volleys
$\{v\}_h$	volleys in interdiction action h
	(h partitions volleys and each volley is part of only one action}
h_v	interdiction action h includes volley v
$\{h\}_a$	actions to interdict attack a
$\{p,g,d\}_v$	Defensive volley v positions platform p in position g to employ defense option d
$\{v\}_p$	set of volleys that might be launched from platform p

New Data [units]

$loadout_{p,i}$	number of type i interceptors carried by platform p [interceptors]
$salvo_{c,d,i}$	platform class c using defense option d launches this number of type i missiles [missiles/engagement]
$epoch\_length$	Planning horizon [time]
$engage\_rate_p$	rate at which platform p can manage engagements [missiles/time]
$\overline{engage}_p$	maximum number of engagements platform p can manage $\equiv \lceil engage\_rate_p * epoch\_length \rceil$ [missiles]

$shoot\_rate_p$	rate at which platform p can shoot interceptors [interceptors/time]
$\overline{shoot}_p$	maximum number of interceptors platform p can shoot $\equiv \lceil shoot\_rate_p * epoch\_length \rceil$ [interceptors]
$capacity_g$	maximum number of platforms allowed at grid position g [platforms]
$Pnul_h$	probability that attack a would be negated by interdiction action $h \in \{h\}_a$ [fraction]
$\widehat{ATTACK}_a$	=1 if attack a launched, =0 otherwise [binary, fixed]

Variables [units]

$PLACE_{p,g}$	1 if platform p is positioned at g, 0 otherwise [binary]
$DEFEND_h$	1 if interdiction action h is used, 0 otherwise [binary]

$$Z_{\min}(\widehat{\mathbf{ATTACK}}) = \min_{\substack{\mathbf{PLACE},\\ \mathbf{DEFEND}}} Z \qquad [D0]$$

$$s.t. \qquad Z \geq$$

$$\sum_{t} value_t \sum_{a \in A_t} Pk_a \left(1 - \sum_{\{h\}_a} Pnul_h DEFEND_h\right) \widehat{ATTACK}_a \qquad [D1]$$

$$\sum_{g} PLACE_{p,g} \leq 1 \qquad \forall p \qquad [D2]$$

$$\sum_{p} PLACE_{p,g} \leq capacity_g \qquad \forall g \qquad [D3]$$

$$\sum_{\substack{\{v\}_p, \{p,g,d\}_v,\\ h_v}} DEFEND_h \leq \left\lceil epoch\_length\, \overline{engage}_p \right\rceil \qquad \forall p \qquad [D4]$$

$$\sum_{\substack{\{v\}_p, \{p,g,d\}_v,\\ h_v, i}} salvo_{c(p),d,i} DEFEND_h \leq \left\lceil epoch\_length\, \overline{shoot}_p \right\rceil \qquad \forall p \qquad [D5]$$

$$\sum_{\substack{\{v\}_p, \{p,g,d\}_v,\\ h_v, i}} salvo_{c(p),d,i} DEFEND_h \leq loadout_{p,i} \qquad \forall p, i \qquad [D6]$$

$$DEFEND_h \leq PLACE_{p,g} \qquad \forall h, \{v\}_h, \{p,g,d\}_v \qquad [D7]$$

$$\sum_{\{h\}_a} DEFEND_h \leq 1 \qquad \forall a \qquad [D8]$$

$$PLACE_{p,g} = PLACE_{p+1,g} \qquad \forall group,\ p \in \{p\}_{group},\ p < \left|\{p\}_{group}\right| \qquad [D9]$$

$$PLACE_{p,g}, DEFEND_h \in \{0,1\} \qquad [D10]$$

Discussion: [D0] introduces the objective, and constraint [D1] defines the objective variable as the minimum upper bound on total expected target damage. [D0] and [D1] are expressed this way to facilitate later decomposition. Each constraint [D2] limits a platform to occupy at most one grid position, each constraint [D3] limits the number of platforms in a grid position, each constraint [D4] limits the number of engagement volleys by a platform during the planning epoch., each constraint [D5] limits the number of launches from each platform, each constraint [D6] limits the total number of launches from a platform by its onboard missile inventory, each constraint [D7] permits launching a defensive interdiction action only if each launching platform participating in this action is positioned in a grid position for its volley. Each constraint [D8] permits at most one interdiction engagement action of an attack a; the selected probability of nullification is communicated to an Attacker model as $\widehat{Pnul_h}$. Each constraint [D9] requires collocation of a pair of platforms in the same group, and variable domains [D10] require binary decisions. Note that constraints [D4] do not require a response for every attack. Indeed, if defenses are overwhelmed, it may be impossible to intercept every attack, and we must allow for this eventuality.

We state the opposing decisions as model MINMAX:

$$Z^* = \min_{\substack{\mathbf{PLACE,}\\ \mathbf{DEFEND}}} \max_{\substack{\mathbf{MOVE,}\\ \mathbf{AVAIL,}\\ \mathbf{ATTACK}}} \sum_t value_t \sum_{a \in A_t} Pk_a \left(1 - \sum_{\{h\}_a} Pnul_h DEFEND_h \right) ATTACK_a$$

$s.t.$ [A1]-[A7] and [D2]-[D10]

We cannot solve MINMAX with conventional techniques, but if we temporarily fix variables $\mathbf{PLACE}$ and $\mathbf{DEFEND}$, the result is a capacitated network flow linear program. Taking the dual of this linear program, and freeing $\mathbf{PLACE}$ and $\mathbf{DEFEND}$, we achieve an integer linear program JD-ILP we can solve with conventional techniques:

MODEL JD-ILP:

$$
\begin{aligned}
Z = \underset{\substack{\alpha,\beta,\gamma,\delta,\\ \underline{\pi},\overline{\pi},\rho,\theta}}{\text{MIN}} \quad & \sum_{m} mobile_m \alpha_m + \sum_{s,m} launches_{s,m} \beta_{s,m} \\
& -\underline{move}_{s,m} \underline{\pi}_{s,m} + \overline{move}_{s,m} \overline{\pi}_{s,m} \\
& +\overline{attacks}_{s,m} \rho_{s,m} + \sum_{t} \overline{missiles}_t \delta_t + \sum_{a} \theta_a
\end{aligned}
$$

$$
\begin{aligned}
\text{s.t.} \quad & \alpha_m - \beta_{s,m} - \underline{\pi}_{s,m} + \overline{\pi}_{s,m} \ge 0 && \forall s,m \quad (MOVE_{s,m}) \quad \text{[T1]} \\
& \beta_{s,m} - \gamma_{s,m} + \rho_{s,m} \ge 0 && \forall s,m \quad (AVAIL_{s,m}) \quad \text{[T2]} \\
& \gamma_{s,m} + \delta_t + \theta_a && \\
& \qquad \ge value_t Pk_{s,m,t} (1 - \sum_{\{h\}_a} Pnul_h) DEFEND_h && \\
& && \forall a, \{s,m,n,t\}_a \\
& && (ATTACK_a) \quad \text{[T3]} \\
& \alpha_m, \beta_{s,m}, \delta_t, \gamma_{s,m}, \underline{\pi}_{s,m}, \overline{\pi}_{s,m}, \theta_a, \rho_{s,m} \ge 0 && \text{[T4]} \\
& \text{and constraints [D2]-[D10]} &&
\end{aligned}
$$

Discussion: This reformulation uses the variables with Greek names introduced with the constraints in AMAX.

The “two-sided” option solves JD-ILP to position SEEN Defender platforms, recovering the corresponding attacker plan by solving AMAX($\widehat{\mathbf{Pnul}}$) with variables $\mathbf{PLACE}$ and $\mathbf{DEFEND}$ fixed to their optimal values, and $\widehat{Pnul}_{\text{a}} \equiv \sum_{\{h\}_a} \text{Pnul}_h DEFEND_h$. Then SECRET Defender platforms are positioned (and SEEN Defenders may change volleys in $\mathbf{DEFEND}$ but not their SEEN positions).

Once all Defender platforms are positioned by $\mathbf{PLACE}^*$, the intercept assignments $\mathbf{DEFEND}$ are re-optimized among defending platforms solving JD-ILP with $\mathbf{PLACE} = \mathbf{PLACE}^*$. I.e., although we admit the attacker can observe SEEN Defender platform positions, we do not reveal Defender intercept assignments.

Regardless of planning option, SHOOTER platforms are positioned to minimize the value of un-intercepted launches in terms of total threatened expected target damage.

JD-ILP can be embellished with additional features as long as the modifications can be expressed linearly in $(\mathbf{PLACE}, \mathbf{DEFEND})$, and the embellishments that modify the attacker's constraints [A1]-[A7] do not destroy their pure network total unimodularity.

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III. IRAN, 2023 SCENARIO

In this scenario, we demonstrate the U.S. military's response to a small-scale attack from Iran. U.S. intelligence advises us of an imminent threat by Iran to attack two enemies perceived to have humiliated them at the United Nations: Poland and Israel have infuriated Iran's leadership, and we are advised their capitals are at acute risk. Accordingly, the U.S. decides to move visible missile defense forces to discourage or, if necessary, thwart these anticipated attacks.

Iran can launch any missile from any launch site. The U.S. military can defend from the attack using a fixed set of interceptors. JDEF returns the defense plan that minimizes the expected damage from the worst-case attack launched by Iran on Warsaw and Tel Aviv, given input attacker and interceptor parameters.

Complete data sets are stored in IRAN.INC, which can be accessed at https://faculty.nps.edu/gbrown/downloads.htm.

A. ATTACKER'S LAUNCH SITES

Our list of Iranian ballistic missile launch sites has been developed from unclassified sources (Federation of American Scientists [FAS] 2016; Global Security [GS] 2020a; Nuclear Threat Initiative [NTI] 2023). These sites are listed in Table 1 and shown in Figure 1.

Table 1. Iranian ballistic missile launch sites. Adapted from FAS (2020), GS (2020a), and NTI (2023).

Launch Site	Latitude	Longitude
Abu Musa	N 25° 52’	E 55° 01’
Aliabad	N 34° 47’	E 51° 05’
Arak	N 34° 05’	E 49° 41’
Bandar Abbas	N 27° 11’	E 56° 16’
Dorud	N 36° 00’	E 51° 29’
Esfahan	N 32° 40’	E 51° 40’
Gamsar	N 35° 40’	E 51° 45’
Gostaresh	N 35° 28’	E 48° 53’
Imam Ali	N 33° 28’	E 48° 21’
Karaj	N 35° 05’	E 51° 00’
Khorramabad	N 33° 28’	E 48° 21’
Lavizan	N 35° 50’	E 51° 29’
Manzariyeh	N 35° 49’	E 51° 28’
Mashhad	N 36° 18’	E 59° 35’
Parchin	N 35° 31’	E 51° 46’
Qeshm	N 26° 57’	E 56° 16’
Semnan	N 35° 34’	E 53° 23’
Shahroud	N 36° 25’	E 55° 00’
Shiraz	N 29° 36’	E 52° 32’
Sirjan	N 29° 27’	E 55° 40’
Sirri Island	N 25° 54’	E 54° 31’
Sultanatabad	N 35° 47’	E 51° 28’
Tabriz	N 38° 05’	E 46° 15’
Tehran	N 35° 40’	E 51° 25’

Coordinates are accurate to approximately 1.6 km.

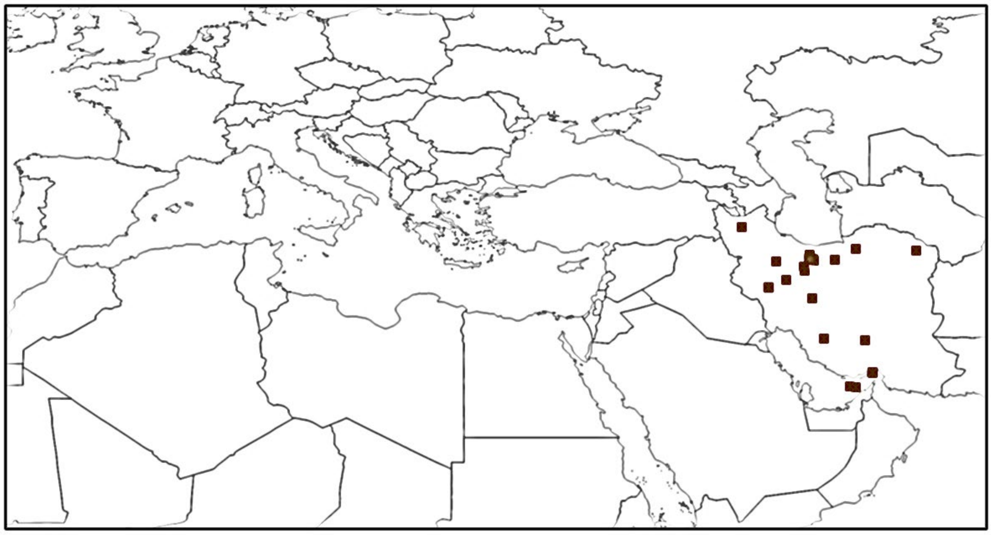


Figure 1. Map of Iranian ballistic missile launch sites. Adapted from FAS (2020), GS (2020a), and NTI (2023).

We conservatively assume each launch site is fully operational and can launch any type of Iranian ballistic missile. Each launch site is limited to a quantity of one missile of each type. The latitudes and longitudes provided are estimates and may not be exact for the locations of the listed launch sites. We do not account for the growing list of mobile launchers in this scenario, including defilade launch positions.

B. ATTACKER'S MISSILES

The missiles currently in Iran's inventory are listed in Table 2. A minimum and maximum range are listed for each missile type.

Table 2. Iranian ballistic missile types with minimum and maximum ranges. Adapted from Jane's (2020a, 2022a, 2022d, 2022h, 2022i, 2023c, 2023d, 2023e).

		Range (est.) [km]	
Missile	**Type**	**Min**	**Max**
Shahab-1	SRBM	50	300
Shahab-2	SRBM	50	550
Qiam-1 HE	SRBM	50	900
Shahab-3/Ghadr-1	MRBM	500	2000
Fateh	SRBM	40	210
Fateh-3	SRBM	40	300
Fateh Hormuz ½	SRBM	40	250
Fateh Zolfaghar	SRBM	40	700
Fateh Dezful	MRBM	40	1000
Fateh Raad-500	SRBM	40	500
Fateh Kheibar Shekan	MRBM	40	1450
Sejil	MRBM	300	2500
Musudan (MRBM)	MRBM	300	2000
Musudan (IRBM)	IRBM	300	3000

As of 2020, most Shahab-3 missiles had been converted to Ghadr-1 missiles (Jane's, 2020d). Therefore, in this scenario, the Shahab-3/Ghadr-1 missile encompasses all earlier Shahab-3 variants. The minimum and maximum ranges shown in Table 2 for the Shahab-3/Ghadr-1 missile group are the minimum and maximum ranges of the Ghadr-1.

The Fateh 110 family of SRBMs and MRBMS includes several variants that are currently in service: Fateh, Fateh-3, Khalij Fars, Hormuz-1/2, Zolfaghar, Fateh Mobin, Dezful, Raad-500, Zolfaghar Basir, and Kheibar Shekan. The estimated minimum range for all variants is 40 km based on Jane's data (Jane's, 2022a). In this scenario, we have included the Khalij Fars variant within the Fateh-3 because it has the same estimated minimum range of 40 km and estimated maximum range of 300 km. The Khalij Fars adds a ship-targeting capability to the Fateh-3 SRBM.

The Fateh Zolfaghar entry in this scenario includes both the Zolfaghar and the Zolfaghar Basir variants. They both have an estimated minimum range of 40 km and an estimated maximum range of 700 km.

In this scenario, we pessimistically assume each attacking missile has an 80% probability of hitting a defended asset if not intercepted. This is a JDEF input that can be adjusted as desired.

C. POTENTIAL TARGETS

The list of potential targets used in this scenario is listed in Table 3.

Table 3. Defended assets targeted by Iran.

Asset	Latitude	Longitude	Value	Max Missiles
Warsaw, Poland	52° 14' N	21° 11' E	10	5
Tel Aviv, Israel	32° 06' N	34° 51' E	2.4	5

Each defended asset is characterized by its location (latitude and longitude), its value in the attack, and the maximum number of missiles that can hit it. Values have been assigned based on population, and then scaled by dividing the city population by 1 million and multiplying by a factor such that the maximum value assigned to any asset is 10. A maximum number of targeted attacking missiles is given.

D. AVAILABLE DEFENSIVE INTERCEPTORS

The list of available defensive interceptors in this scenario is given in Table 4. This list does not encompass the U.S.'s full ballistic defense capability. It is intended to demonstrate how the U.S. can optimally prepare for threatened Iranian ballistic missile attacks given a fixed set of defensive interceptors. In our scenario, we assume all candidate interceptors equipped with AEGIS use the U.S. Navy Standard Missile 3 (SM-3). This can be adjusted in the JDEF inputs to include the U.S. Navy Standard Missile 2, or any other type of missile, if desired by the planner.

Table 4. Available U.S. interceptors in Iran scenario. Adapted from Jane's (2020c, 2021, 2022i, 2022j, 2023a).

Interceptor Type	Launching platform	Maximum Range (km)	Max Speed (approx.)	Interdiction Type
Tomahawk Land Attack Missile (TLAM)	Airborne, ground, ship, submarine	2500	918 km/hour	Strike
Conventional Prompt Strike (CPS)	Mobile, ground, ship, submarine	2775	Mach 5	Strike
ALCM	Airborne	2500	800 km/hour	Strike
THAAD	Mobile	190	10,080 km/ hour	Exo-Atmospheric
PAC-2	Mobile	160	4284 km/hour	Terminal
GEM	Mobile	160	4284 km/hour	Terminal
PAC-3	Mobile	20 ballistic target; 70 aerial target	Unknown	Terminal
PAC-3 MSE	Mobile	35 ballistic target; 100 aerial target	Unknown	Terminal
SM-3	Ground, ship	1200	Mach 3	Exo-Atmospheric
Carrier Air Wing (CVW)	Ship	600	Mach 1.8	Strike

Interceptors are classified by launching platform, maximum ranges, maximum speed achieved by the interceptor, and interdiction type. Strike missiles are targeted at attacking missile launch sites, exo-atmospheric interceptors attempt interception during mid-flight of an attacking missile, while terminal interceptors defend in the last stage of an attacking missile approaching a defended asset target. The conventional prompt strike (CPS) missile is representative of several U.S. hypersonic strike missiles in development. The aircraft within CVWs demonstrate aircraft carrier (CVN) strike capabilities and are treated as ship-launched interceptors. We assume each aircraft has a strike range of 600 km.

The defensive interceptors and strike missiles in Table 4 are not stand-alone entities and must be launched from defensive platforms. The U.S. military has a subset of defensive platforms available for use in this scenario (Table 5). Each defensive platform is equipped with a subset of these defensive weapons. Some defending platforms must use radar to get an interception solution, and are thus visible to the adversary (SEEN in Table 5).

Some defenders either use attacking launch site coordinates with no radar identification, or maintain radiation silence and depend on sister defenders for cues to attempt interception (SECRET in Table 5). Terminal defenders Patriot and THAAD are essentially collocated with defended assets and we assume easily located by our adversary (SEEN in Table 5).

Table 5. Available U.S. defender platforms in Iran scenario. Adapted from Jane's (2022i).

Platform	**SEEN/ SECRET**	**Number Available**	**Preferred Interceptor Type**	**Interceptor Quantity (per platform)**
Destroyer (DDG)	SEEN	2	SM-3	10
Cruiser (CG)	SEEN	1	SM-3	20
Aircraft Carrier (CVN)	SEEN	1	CVW	80
Fast Attack Submarine (SSN)	SECRET	1	CPS, TLAM	10
B-52 Bomber	SECRET	1	ALCM	24
Patriot Battery	SEEN	2	PAC-3	6 launchers x 16 missiles per launcher
THAAD Battery	SEEN	1	THAAD	10
AEGIS Ashore	SEEN	2	SM-3	24

We assume each Patriot battery is equipped with as many as 16 launchers each with 6 PAC-3 missiles. Patriot batteries can also accommodate 4–6 launchers of 4 PAC-2/PAC-2 GEM missiles or 4–6 launchers of 6 PAC-3 MSE missiles. SM-3 quantities are estimates and depend on the amount of other missiles ships carry. Due to the classified nature of the SSNs and B-52s, missile quantities are also estimates.

E. POTENTIAL DEFENSIVE INTERCEPTOR LOCATIONS

JDEF requires that the planner provide a set of potential defensive interceptor locations for each platform. Potential locations are broken down by interceptor type. One CVN, one CG, and two DDGs comprise a carrier strike group (CSG) for this scenario. Interceptors in the CSG must be positioned together and we do not allow DDGs and CGs to operate independently of the CSG. Because of Iran's anti-ship anti-submarine capabilities, CSGs and SSNs are limited to positions in the Eastern Mediterranean or Northern Arabian Gulf (Table 6). We do not allow for CSGs and SSNs to be positioned in the Gulf of Oman in this scenario. If we position CSGs and SSNs closer to Iran during a situation in which we expect our CSGs and SSNs to fire missiles into Iran, our interceptors will be vulnerable to anti-ship and/or anti-submarine missiles and naval auxiliary small boat attack. In this scenario, we fix the CSG's location in the Eastern Mediterranean.

Table 6. Candidate CSG and SSN launch locations in Iran scenario.

	Location	
	Latitude	Longitude
1	33° 01' N	33° 43' E
2	35° 30' N	31° 00' E
3	35° 19' N	29° 46' E
4	36° 05' N	25° 27' E
5	22° 01' N	64° 18' E
6	35° 49' N	19° 12' E

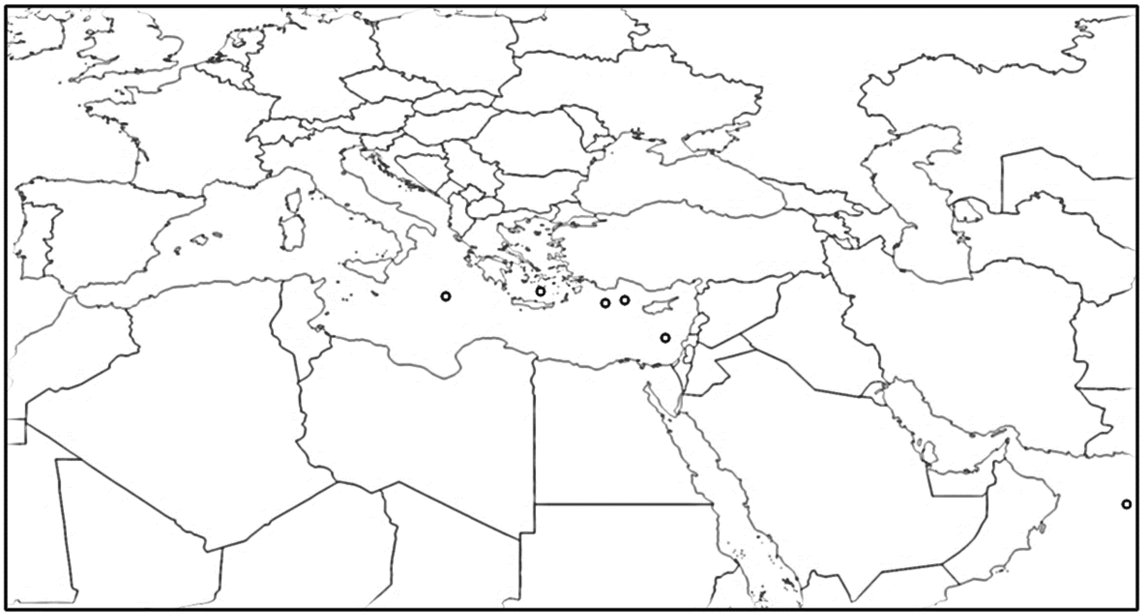


Figure 2. Map of candidate CSG and SSN launch locations in Iran scenario.

We do not restrict candidate B-52 locations as we do for CSG and SSNs. These locations have been chosen strategically. Candidate B-52 locations are listed in Table 7 and shown in Figure 3.

Table 7. Candidate B-52 locations in Iran scenario.

	Location	
	Latitude	Longitude
1	29° 12’ N	49° 15’ E
2	28° 05’ N	50° 10’ E
3	27° 07’ N	51° 08’ E
4	42° 04’ N	40° 13’ E
5	42° 57’ N	33° 36’ E
6	42° 27’ N	30° 17’ E
7	42° 04’ N	37° 17’ E
8	33° 01’ N	33° 43’ E
9	35° 30’ N	31° 00’ E
10	35° 19’ N	29° 46’ E
11	36° 05’ N	25° 27’ E
12	40° 41’ N	25° 08’ E
13	44° 52’ N	31° 03’ E
14	43° 58’ N	36° 31’ E
15	41° 42’ N	17° 5’ E
16	35° 49’ N	19° 12’ E
17	44° 03’ N	24° 23’ E
18	49° 05’ N	26° 40’ E

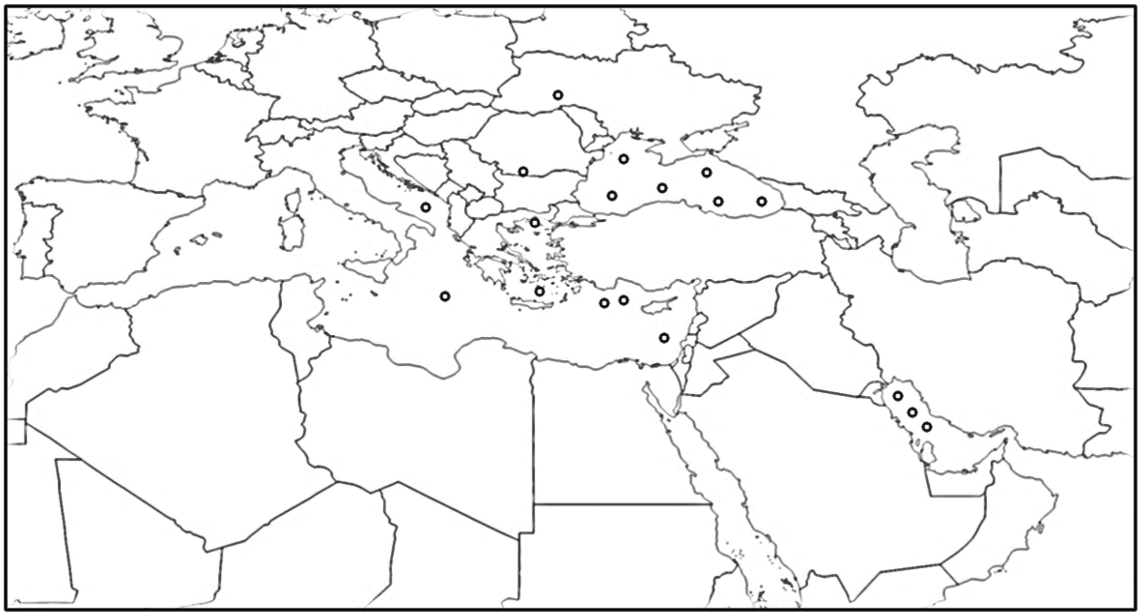


Figure 3. Map of candidate B-52 launch locations in Iran scenario.

The U.S. currently has two AEGIS Ashore systems in commission: one located in Deveselu, Romania, and another located in Redzikowo, Poland. The locations of these installations are fixed and we do not allow JDEF to re-locate these platforms. JDEF chooses to located Patriot batteries and THAAD batteries close by a defended asset. We assume these interceptors can be easily moved to alternate locations at JDEF's recommendation.

F. RESULTS

JD-ILP solves two sets of models: JD-ILP for SEEN defenders and DEFENDER for SECRET defenders. JD-ILP for SEEN defenders has 999 constraints, 556 continuous variables, and 631 binary variables. DEFENDER for SECRET defenders has 1,503 constraints, 2 continuous variables, and 1,425 binary variables. Both models solve in 9 seconds to an integer convergence tolerance (the difference between the solution reported and the bound on how much better of a solution might exist) of 5%.

Iran's optimal attack plan and corresponding U.S. interceptor assignments are shown in Table 8. These results are from a Dell Precision 7920 Tower with 128GB random access memory and a Passmark (2023) rating of 3188.

Table 8. Optimal opposing Iran attack and U.S. defense plans—the best worst case for each opponent.

Attack Number	Asset	Launch Site	Missile Type	Probability of Nullification	Expected Damage	Defender Class	Interceptor Type	Interceptor Salvo
1	Tel Aviv	Abu Musa	Musudan (IRBM)	1.0	0	B-52	ALCM	1
2	Tel Aviv	Bandar Abbas	Sejil	0.61	0.7488	CG	SM-3	1
3	Tel Aviv	Bandar Abbas	Musudan (IRBM)	1.0	0	B-52	ALCM	1
4	Tel Aviv	Esfahan	Ghadr-1	0.61	0.7488	CG	SM-3	1
5	Tel Aviv	Gamsar	Ghadr-1	0.61	0.7488	CG	SM-3	1
6	Warsaw	Tabriz	Sejil	0.81	1.52	Patriot 1	PAC-3	1
7	Warsaw	Tabriz	Musudan (IRBM)	0.81	1.52	Patriot 1	PAC-3	1
8	Warsaw	Dorud	Musudan (IRBM)	0.81	1.52	Patriot 2	PAC-3	1
9	Warsaw	Gostaresh	Musudan (IRBM)	0.81	1.52	Patriot 1	PAC-3	1
10	Warsaw	Manzaryieh	Musudan (IRBM)	0.81	1.52	Patriot 1	PAC-3	1

Expected damage is a function of asset value, probability of kill for each attacking missile type (80% for this scenario), and probability of nullification and/or intercept (which varies by intercepting missile type). The probability of interception is the probability that an attack is nullified (interdicted) by an interceptor and come from the cross-range, down-range table inputs.

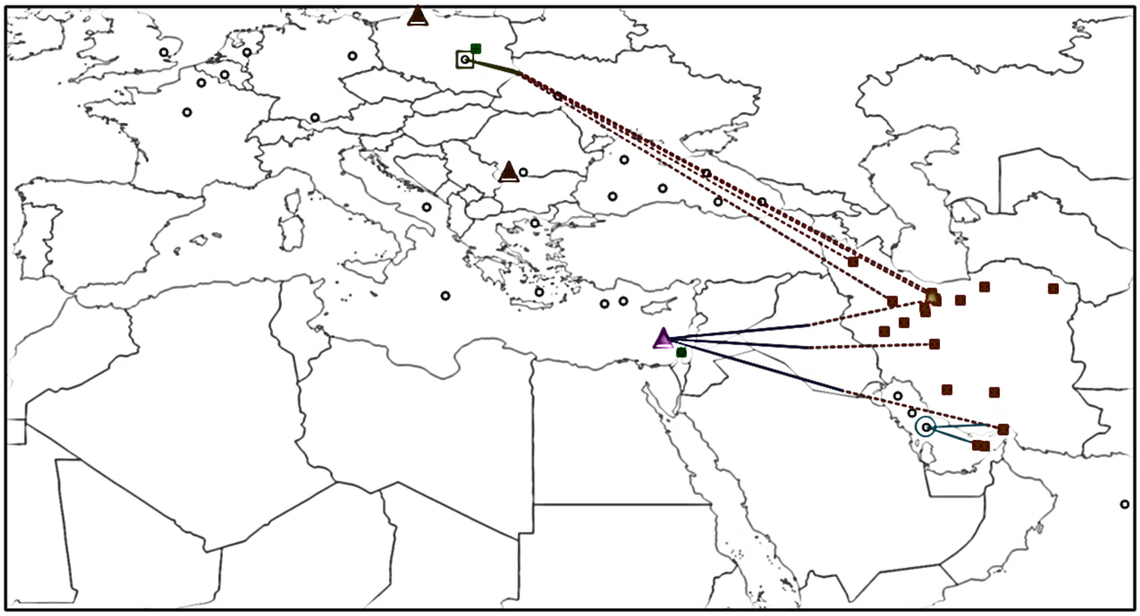
All attacking missiles are engaged by an interceptor (i.e., there is no “leaker”). Attacks number 2 and 4 will be neutralized. All other attacks have probability of nullification less than one but greater than zero.

Table 9 provides a breakdown of defender locations. Optimal attack and defense plans are shown in Figure 4.

Table 9. U.S. defender location assignments in Iran scenario.

Defender Class	**Platform**	**Group**	**SEEN/SECRET**	**Position**	
				Latitude	Longitude
CVN	CVN	CSG	SEEN	35° 30’ N	31° 00’ E
CG	CG				
DDG	DDG 1				
	DDG 2				
B-52	B-52	-	SECRET	27° 07’ N	51° 08’ E
AEGIS	AEGIS Ashore 1	-	SEEN	44° 03’ N	23° 25’ E
	AEGIS Ashore 2	-	SEEN	54° 28’ N	17° 23’ E
Patriot	Patriot 1	-	SEEN	51° 30’ N	20° 30’ E
	Patriot 2	-			

AEGIS Ashore system locations are fixed. Interceptors not assigned to an attack are not included in this table unless their locations are fixed.



Square dots within Iran's borders represent Iranian missile launch sites. Dashed lines emanating from the launch sites represent Iranian missile attacks. Larger square, triangular, and circular shapes represent defenders. The solid lines emanating from the shapes represent intercepting missile trajectory. All other hollow circular dots are candidate interceptor locations.

Figure 4. Optimal attack and defense plans suggested by JDEF for the Iran scenario.

The optimal defense plan reduces the maximum expected damage by 97.2%, where maximum expected damage is the damage incurred with no defense. JDEF does not assign locations to all provided interceptors for this scenario, which suggests that adding the unassigned interceptors (under the current assumptions of potential interceptor locations and interceptor cross-range, down-range data) does not provide advantage to U.S. forces. While the B-52 is the only strike platform assigned to an attack in this scenario, it can be optimally positioned to engage two different attacks (attack numbers 1 and 3) and is therefore crucial in protecting Tel Aviv.

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IV. NORTH KOREA, 2023 SCENARIO

North Korea presents a persistent threat to many of its US-allied neighbors. Here we provide a net assessment of the scope of missile defense we can provide if cued that this adversary is preparing launches. Complete data sets are stored in NK.INC, which can be accessed at: https://faculty.nps.edu/gbrown/downloads.htm.

A. ATTACKER'S LAUNCH SITES

Our list of North Korean ballistic missile launch sites has been developed from unclassified sources (FAS 2016; GS 2020b; NTI 2023). This list is likely not comprehensive, but it represents North Korea's capabilities as of April 2023.

Table 10. Known North Korean launch sites. Adapted from FAS (2016), GS (2020b), and NTI (2023).

Launch Site	Latitude	Longitude
Chunggang-up	N 38° 37’	E 126° 41’
Chiha-ri	N 41° 46’	E 126° 53’
Hamhung	N 39° 49’	E 127° 40’
Hodo	N 39° 24’	E 127° 32’
Kanggamchan	N 40° 24’	E 125° 12’
Kanggye	N 40° 58’	E 126° 35’
Kumchon-ni	N 38° 57’	E 127° 32’
Man’gyongdae-ri	N 38° 59’	E 125° 08’
Mayang	N 40° 00’	E 128° 11’
Namgung-ni	N 39° 08’	E 125° 46’
No-dong	N 40° 50’	E 129° 40’
Ok’pyong-nodongjagu	N 39° 17’	E 127° 18’
Paegun	N 39° 58’	E 124° 35’
Pyongyang	N 39° 00’	E 125° 45’
Sangum-ri	N 39° 08’	E 127° 37’
Sangwon	N 38° 50’	E 126° 05’
Sil-li	N 39° 12’	E 125° 40’
Sohae	N 39° 40’	E 124° 42’
Sunchon	N 39° 25’	E 125° 55’
Tokch’on-Kun	N 39° 45’	E 126° 15’
Toksong-gun	N 40° 25’	E 128° 10’
Tonghae Satellite Launching Ground (Musudan-ri)	N 40° 51’	E 129° 40’
Wonsan	N 39° 10’	E 127° 29’
Yangdok	N 39° 17’	E 126° 48’
Yongo-dong	N 41° 59’	E 129° 58’

Coordinates are accurate to approximately 1.6 km.

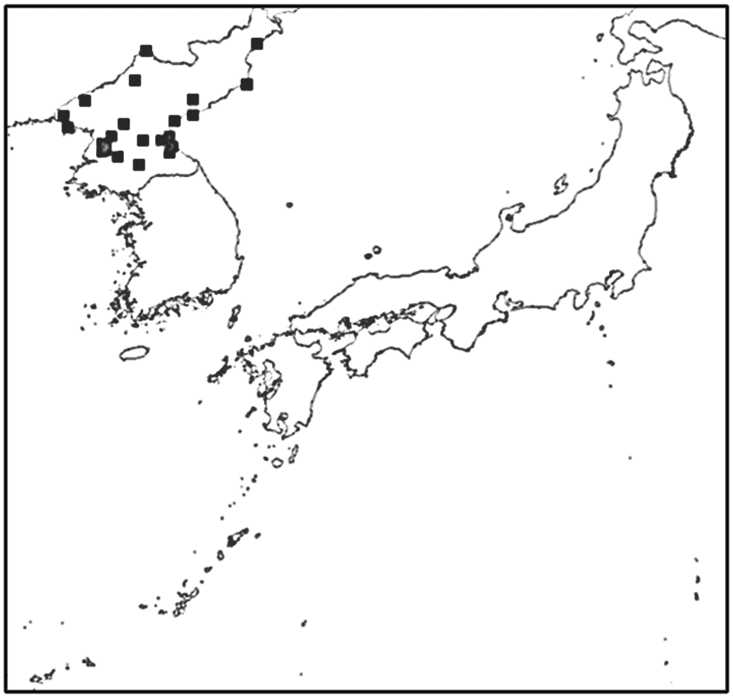


Figure 5. Map of known North Korean launch sites.

We assume that each launch site is fully operational and has the ability to launch all types of North Korean ballistic missiles. We assume all launch sites have an inventory of one missile of each type that might be ready to launch at once. These are inputs to JDEF that can be adjusted by the planner. (For instance, JDEF allows the planner to introduce mobile missiles that can be shuttled around by the attacker at will.) The latitude and longitudes provided in Table 10 are close estimates, accurate to just less than 2 km.

B. ATTACKER'S MISSILES

The missiles in North Korea's inventory are listed in Table 11.

Table 11. Types of North Korean ballistic missiles. Adapted from Jane's (2022b, 2022c, 2022d, 2022e, 2022f, 2023b, 2023c) and Center for Strategic and International Studies [CSIS] (2022).

Missile	Class	Range (km)	
		Min	Max
Hwaseong-5 Scud B	SRBM	50	300
Hwaseong-6 Scud C	SRBM	50	500
Hwaseong-9 Scud ER	MRBM	50	1000
Hwaseong-10 Musudan	IRBM	2500	4000
Hwaseong-12	IRBM	1000	4500
KN-25	SRBM	50	380
No Dong 1 (Hwaseong-7)	MRBM	400	1300
No Dong 2	MRBM	400	1500
Pukguksong-2 KN-15	MRBM	1200	2000

Minimum and maximum ranges are worst-case estimates based on intelligence provided in Jane's. All listed missiles are in service, but exact quantities are unknown. The North Korean Pukkuksong SLBM variants KN-11 and KN-26, remain in development and are not included in this scenario.

In this scenario, we pessimistically assume each attacking missile has an 80% probability of hitting a defended asset if not intercepted. This is a JDEF input that can be adjusted by missile type as desired.

C. POTENTIAL TARGETS

The potential targets used in this scenario are shown in Table 12. Potential targets may include any defended U.S. or ally asset within reach of North Korean ballistic missiles.

Table 12. Defended assets targeted by North Korea.

Asset	Latitude	Longitude	Value	Max Missiles
Hiroshima, Japan	34° 24’ N	132° 27’ E	1.2	5
Naval Base Guam	13° 26’ N	144° 39’ E	10	5
Seoul, South Korea	37° 31’ N	127° 03’ E	9.7	5
Yokosuka, Japan	35° 16’ N	139° 40’ E	10	5

All assets are assigned a value scaled by city population, with a maximum value of 10. Assets with naval bases are automatically assigned a value of 10. Each asset is characterized by the maximum number of missiles we assume would be directed to hit it. For this scenario, we have chosen to set this maximum number of missiles to 5.

D. AVAILABLE DEFENSIVE INTERCEPTORS

Our set of available defensive interceptors for this scenario is the same as for the Iran scenario (Table 4).

Due to the large scale of the planned attack from North Korea, the U.S. has allocated more defender classes (platforms) to improve our chances of intercepting the attacks. We are now allowed 2 CSGs, 2 SSNs, 2 B-52s, 2 Patriot batteries, and 2 THAAD batteries.

E. POTENTIAL DEFENSIVE INTERCEPTOR LOCATIONS

Potential locations are broken down by defender type. For this scenario, we only allow two candidate CSG locations (Table 13), but this can be adjusted by the planner as desired. CSGs are fixed in tactically advantageous locations such that they are not judged to be seriously vulnerable to counter-attack. These positions also allow for them to be used for mission assignments other than missile defense.

Table 13. Candidate CSG locations in North Korea scenario.

	Location	
	Latitude	Longitude
1	37° 44’ N	131° 56’ E
2	36° 48’ N	131° 52’ E

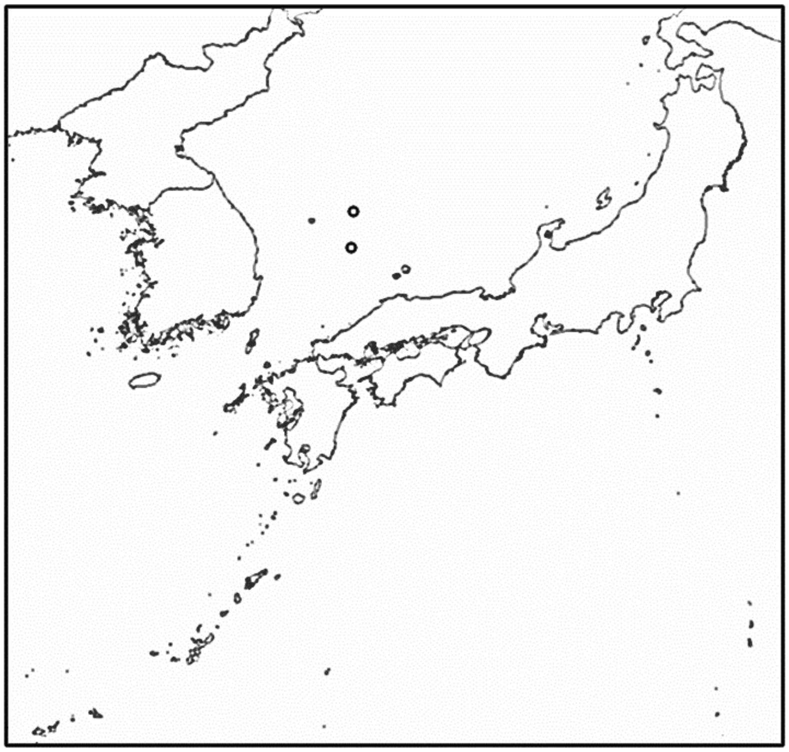


Figure 6. Map of candidate CSG launch locations in North Korea scenario, shown by the two small circles in the Sea of Japan.

Because North Korea does not have extensive anti-submarine capabilities, potential locations of our SSNs are not heavily restricted, and can be positioned in any location around North Korea or defended assets that is advantageous to counter a missile attack. Candidate SSN locations in this scenario are listed in Table 14 and shown in Figure 7.

Table 14. Candidate SSN launch locations in North Korea scenario.

	Location	
	Latitude	Longitude
1	25° 30’ N	134° 02’ E
2	12° 47’ N	114° 18’ E
3	32° 40’ N	128° 17’ E
4	40° 44’ N	150° 46’ E
5	29° 11’ N	125° 33’ E
6	35° 11’ N	123° 17’ E
7	21° 58’ N	122° 53’ E
8	31° 05’ N	134° 29’ E
9	32° 52’ N	123° 57’ E
10	37° 44’ N	131° 56’ E
11	20° 05’ N	160° 51’ W
12	21° 45’ N	162° 25’ W
13	20° 05’ N	160° 51’ W
14	13° 36’ N	144° 38’ E
15	38° 57’ N	134° 07’ E
16	31° 21’ N	126° 25’ E
17	40° 09’ N	137° 03’ E
18	33° 08’ N	129° 37’ E
19	39° 18’ N	130° 29’ E
20	41° 42’ N	129° 37’ E
21	39° 30’ N	129° 22’ E

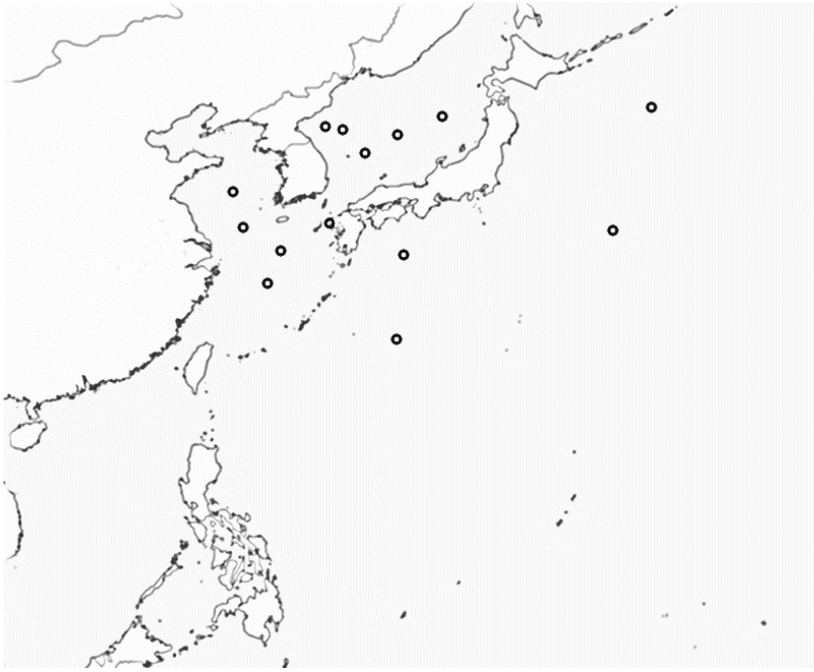


Figure 7. Map of candidate SSN launch locations in North Korea scenario.

THAAD and Patriot batteries are terminal defenders and must be located near defended assets (Table 13). We have chosen THAAD and Patriot locations such that each defended asset has one candidate Patriot and THAAD location no more than 50 km from the coordinates listed in Table 13. Additionally, there is a Patriot battery currently located in Soseongri, South Korea, so we assume Patriot and THAAD batteries can also be positioned there. Potential THAAD and Patriot battery locations are shown in Figure 8.

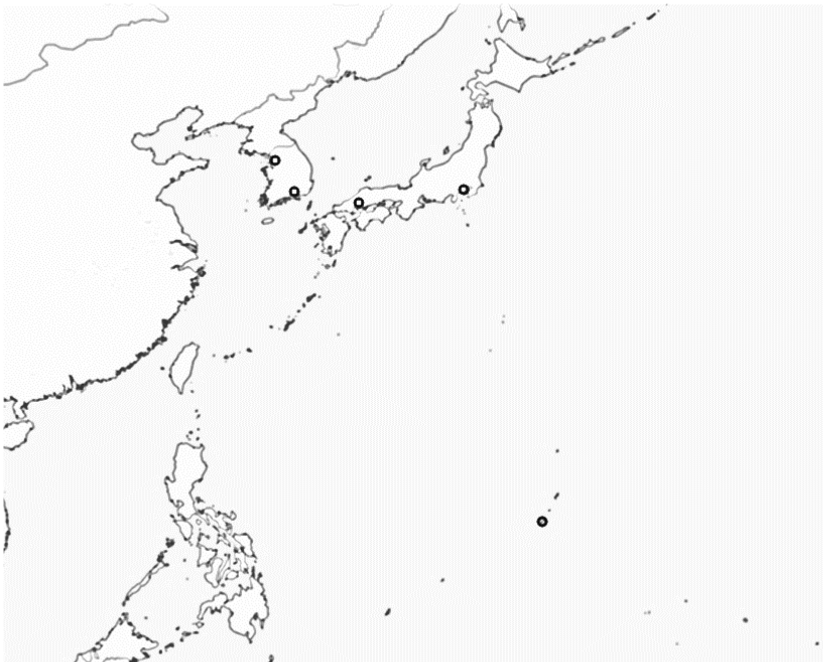


Figure 8. Map of candidate Patriot and THAAD battery launch locations in North Korea scenario.

For simplicity, we let B-52s be positioned in any location suitable for an SSN (Table 14), THAAD, or Patriot (Figure 8).

F. RESULTS

JD-ILP for SEEN defenders has 7,247 constraints, 1,307 continuous variables, and 6,309 binary variables. DEFENDER for SECRET defenders has 1,503 constraints, 2 continuous variables, and 1,425 binary variables. The two-sided integer linear program JD-

ILP has 19,832 constraints, 2 continuous variables, and 19,571 binary variables. Both models solve in 31 minutes to an integer convergence tolerance of 5%.

North Korea's optimal attack plan and corresponding U.S. interceptor assignments are provided in Table 15. Table 16 provides a breakdown of the suggested interceptor positions.

Table 15. Optimal opposing North Korea attack and U.S. defense plans—the best worst case for each opponent.

Attack Number	Asset	Launch Site	Missile Type	Probability of Nullification	Expected Damage	Defender Class	Interceptor Type	Interceptor Salvo
1	Guam Naval Base	Kanggamchan	Hwaseong 12	1.0	0	SSN	CPS	1
2	Guam Naval Base	Mangyongdaeri	Hwaseong 12	1.0	0	SSN	CPS	1
3	Guam Naval Base	Pyongyang	Hwaseong 12	1.0	0	B-52	ALCM	1
4	Guam Naval Base	Sohae	Hwaseong 12	1.0	0	B-52	ALCM	1
5	Guam Naval Base	Tonghae	Hwaseong 12	1.0	0	CVN	CVW	1
6	Hiroshima	Mayang	No Dong 1	0.964	0.0347	DDG	SM-3	2
7	Hiroshima	Ok'pyong-nodongjagu	Musudan	0.964	0.0347	CG	SM-3	2
8	Hiroshima	Sunchon	Musudan	0.964	0.0347	DDG	SM-3	2
9	Hiroshima	Toksonggun	No Dong 1	0.964	0.0347	CG	SM-3	2
10	Hiroshima	Sangumri	No Dong 1	0.964	0.0347	DDG	SM-3	2
11*	Seoul	Mangyongdaeri	KN-25	0	7.76	-	-	-
12*	Seoul	Ok'pyong-nodongjagu	KN-25	0	7.76	-	-	-
13*	Seoul	TokchonKun	Hwaseong-5	0	7.76	-	-	-
14*	Seoul	Hodo	KN-25	0	7.76	-	-	-
15*	Seoul	Sohae	KN-25	0	7.76	-	-	-
16	Yokosukua	Chihari	Musudan	0.964	0.2888	DDG	SM-3	2
17	Yokosukua	Kangye	No Dong 2	1.0	0	SSN	CPS	1
18	Yokosukua	Mayang	No Dong 2	1.0	0	B-52	ALCM	1
19	Yokosukua	Ok'pyong-nodongjagu	No Dong 2	1.0	0	SSN	CPS	1
20	Yokosukua	Paegun	No Dong 2	1.0	0	B-52	ALCM	1

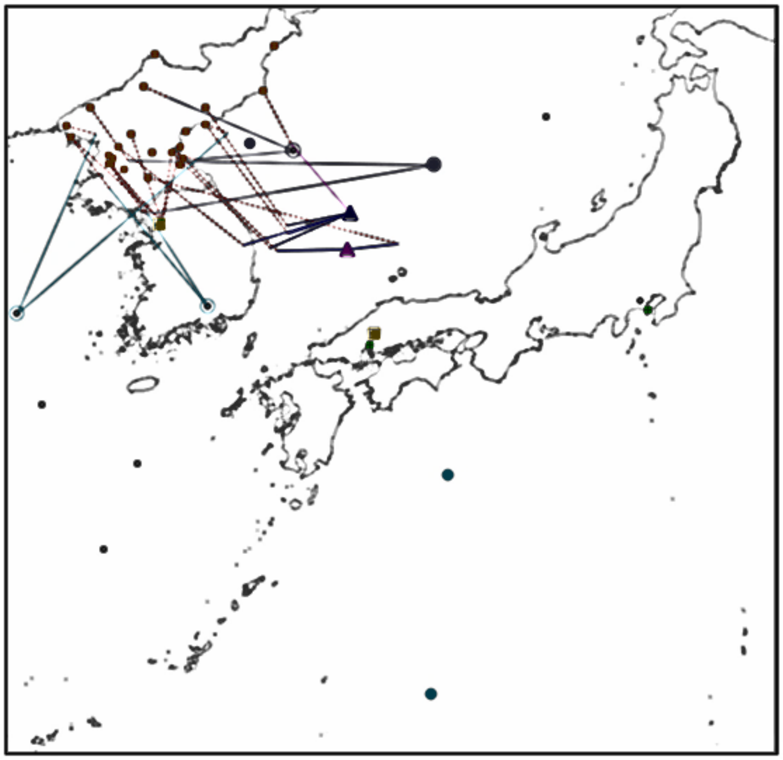
A (*) next to the attack number indicates that the attacking missile is a "leaker" and is not engaged by any defensive interceptors.

Table 16. U.S. interceptor location assignments in North Korea scenario.

Defender Class	Platform	Group	SEEN/SECRET	Position	
				Latitude	Longitude
CVN	CVN 1	CSG 1	SEEN	37° 44’ N	131° 56’ E
CG	CG 1				
DDG	DDG 1				
	DDG 2				
CVN	CVN 2	CSG 2	SEEN	36° 48’ N	131° 52’ E
CG	CG 2				
DDG	DDG 3				
	DDG 4				
B-52	B-52 1	-	SECRET	35° 20’ N	129° 15’ E
	B-52 2			35° 11’ N	123° 17’ E
SSN	SSN 1	-	SECRET	39° 18’ N	130° 29’ E
	SSN 2			38° 57’ N	134° 07’ E
THAAD	THAAD 1	-	SEEN	37° 25’ N	127° 00’ E
	THAAD 2			34° 38’ N	132° 35’ E

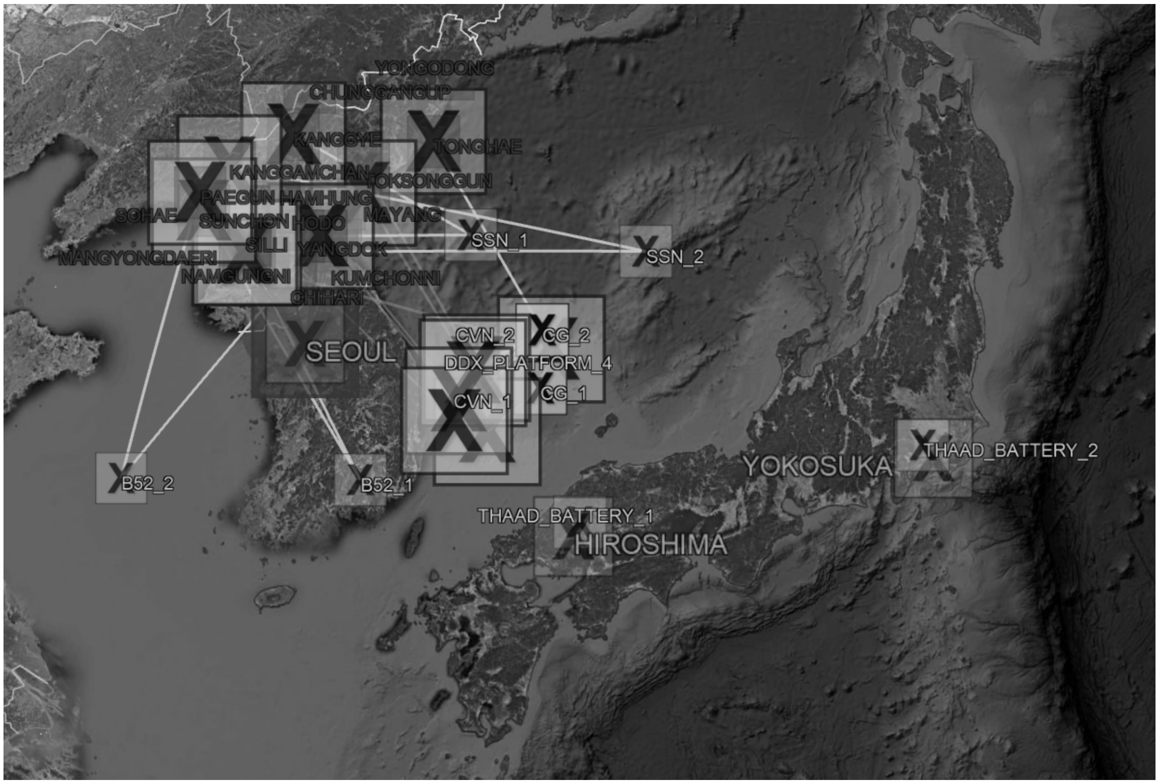
Interceptors not assigned to an attack are not included in this table unless their locations are fixed.

Optimal attack and defense plans are shown in Figure 9. Figure 10 provides a more descriptive interface for interpreting the defense plan.



Square dots within North Korea's borders represent North Korean missile launch sites. Dashed lines emanating from the launch sites represent North Korean missile attacks. Larger square, triangular, and circular shapes represent defenders. The solid lines emanating from the shapes represent intercepting missile trajectory. All other hollow circular dots are candidate interceptor locations.

Figure 9. Optimal attack and defense plans suggested by JDEF for North Korea scenario.



A large box with an X indicates a defended asset, a leaking missile, or an interdiction of an attack. A line indicates a launched attack or a launched interdiction. A small box with an X indicates an optimal defender position. Although this static image is very cluttered, the advantage of JDEF's Google Earth interface is the ability to fly over and drill down to visualize the solution in as much detail as the planner desires.

Figure 10. Snapshot Google Earth (2023) visualization of optimal attack and defense plans suggested by JDEF for North Korea scenario.

An interactive version of Figure 10 can be found in NK_DISPLAY.kml at https://faculty.nps.edu/gbrown/downloads.htm.

In this scenario, North Korea is able to evade U.S. defenders in a set of attacks on Seoul. Five attacking missiles are not engaged by a defender and are expected to strike Seoul. However, defenders within range of attacking missiles are fully engaged, and any unassigned interceptor will be unable to engage attacking missiles while restricted to our current potential interceptor locations and interceptor cross-range, down-range inputs. Our recommended defense plan relies heavily on strike-capable interceptors. Patriot batteries to combat this attack have been mounted and are ready for defense, but are not used in this scenario.

Using the two-sided dual-ILP, JDEF's recommended interceptor positions yield an 89.3% reduction in the maximum expected damage. Given the scale of this suspected attack, JDEF provides a strong initial defense plan, albeit with five leakers striking SEOUL. The planner can either "fix" desired assignments, or set them as "try" assignments to be evaluated in further model excursions (potentially with additional defender platforms and/or missiles made available).

V. CONCLUSION

JDEF's recommended optimal defense plans for the Iran and North Korea scenarios greatly reduce expected damage from potential attacks on our sets of defended assets. In both scenarios, JDEF recommends positions for a broad range of defensive platforms and demonstrates the scope of the U.S.'s theater ballistic missile defense capabilities.

Our application of JDEF in two scenarios of differing sizes demonstrates the model's flexibility. Regardless of whether a country launches a small-scale or large-scale attack, JDEF can recommend an optimal defense plan within reasonable solve times. While an attack launched at four different assets by one country is unlikely, a scenario as such demonstrates how JDEF's capabilities are not impacted by the size of the problem. JDEF can effectively handle threats posed by different types of missiles launching from different locations relative to interceptor locations. Adjusting candidate interceptor locations and potential interceptors, along with all other JDEF inputs, can be accomplished quickly by the planner.

JDEF has the ability to handle strike-capable platforms. As demonstrated in our North Korea scenario, planning for strikes against missile launch sites is crucial to modern missile defense. Effective placement of CVNs and SSNs, along with other strike-capable platforms, can provide us with an advantage against any potential enemy.

In addition to the latitudes and longitudes for optimal defender placement, JDEF also provides the planner with an interactive map that visualizes optimal defender placement and potential launch trajectories of both attacking missiles and interceptors. This interactive Google Earth (2023) map allows the planner to view optimal attack and defense plans in detail, and can help the planner more thoroughly understand both the threats posed by certain enemies and the U.S.'s missile defense capabilities.

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