DEPARTMENT OF DEFENSE ENERGY AND LOGISTICS:
Implications of Historic and Future Cost, Risk, and Capability Analysis

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Abstract

Every year the DoD spends billions satisfying its large petroleum demand. This spending is highly sensitive to uncontrollable and poorly understood market forces. Additionally, while some stakeholders may not prioritize its monetary cost and risk, energy is fundamentally coupled to other critical factors. Energy, operational capability, and logistics are heavily intertwined and dependent on uncertain security environment and technology futures. These components and their relationships are less understood. Without better characterization, future capabilities may be significantly limited by present-day acquisition decisions.

One attempt to demonstrate these costs and risks to decision makers has been through a metric known as the Fully Burdened Cost of Energy (FBCE). FBCE is defined as the commodity price for fuel plus many of these hidden costs. The metric encouraged a valuable conversation and is still required by law. However, most FBCE development stopped before the lessons from that conversation were incorporated. Current implementation is easy to employ but creates little value. Properly characterizing the costs and risks of energy and putting them in a useful tradespace requires a new framework.

This research aims to highlight energy's complex role in many aspects of military operations, the critical need to incorporate it in decisions, and a novel framework to do so. It is broken into five parts. The first describes the motivation behind FBCE, the limits of current implementation, and outlines a new framework that aids decisions. Respectively, the second, third, and fourth present a historic analysis of the connections between military capabilities and energy, analyze the recent evolution of this conversation within the DoD, and pull the historic analysis into a revised framework. The final part quantifies the potential impacts of deeply

uncertain futures and technological development and introduces an expanded framework that brings capability, energy, and their uncertainty into the same tradespace.

The work presented is intended to inform better policies and investment decisions for military acquisitions. The discussion highlights areas within the DoD's understanding of energy that could improve or whose development has faltered. The new metric discussed allows the DoD to better manage and plan for long-term energy-related costs and risk.

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Acronyms and Abbreviations

ADP	Assured Delivery Price
AEPI	Army Environmental Policy Institute
AFTOC	Air Force Total Ownership Cost
AMSAA	Army Materiel Systems Analysis Activity
AoA	Analysis of Alternatives
ASN(EI&E)	Assistant Secretary of the Navy for Energy, Installations, and Environment
ASN(RD&A)	Assistant Secretary of the Navy for Research, Development, and Acquisitions
AT&L	Acquisition, Technology and Logistics
BBP	Better Buying Power
CAMS-ME	Capital Asset Management System
CASCOM	Combined Arms Support Command
CAT	Caterpillar
CERP	Commander's Energy Readiness Program
CJSCI	Chairmen of the Joint Chiefs of Staff
CMC	Commandant of the Marine Corps
CNO	Chief of Naval Operations
CRS	Congressional Research Service
DAG	Defense Acquisition Guidebook
DASA-CE	Deputy Assistant Secretary of the Army for Cost and Economics
DASN	Deputy Assistant Secretary of the Navy
DAU	Defense Acquisition University
DCAPE	Director of Cost Assessment and Program Evaluation
DESC	Defense Energy Support Center
DLA-E	Defense Logistics Agency-Energy
DoDD	Department of Defense Directive
DoDI	Department of Defense Instruction
DOEB	Defense Operational Energy Board
DoN	Department of Navy
DSB	Defense Science Board
DUSD (I&E)	Deputy Under Secretary of Defense (Installations and Environment)
E2O	Expeditionary Energy Office
E2W2	Expeditionary, Energy, Water, and Waste
EIA	Energy Information Administration
EI&E	Energy, Installations, and Environment
EN-ACQT	Navy Operational Energy in Acquisition Team
EP	Energy Performance

ESA	Energy Supportability Analysis
ExFOB	Experimental Forward Operating Base
FBC	Fully Burdened Cost
FBCE	Fully Burdened Cost of Energy
FBCF	Fully Burdened Cost of Fuel
FORCES	Force and Organization Cost Estimating System
ICD	Initial Capabilities Document
JCIDS	Joint Capabilities Integration and Development System
JROC	Joint Requirements Oversight Council
JSTARS	Joint Surveillance and Target Attack Radar System
KPP	Key Performance Parameter
KSA	Key System Attributes
LCC	Life Cycle Costs
LIA	Logistics Innovation Agency
MAGTF	Marine Air Ground Task Force
MARCORPS	Marine Corps System Command
MCO	Marine Corps Order
MDAP	Major Defense Acquisition Program
MPEM	MAGTF Power and Energy Model
MROC	Marine Requirements Oversight Council
NAVAIR	Naval Air Systems Command
NAVSEA	Naval Sea Systems Command
NDAA	National Defense Authorization Act
NPS	Navy Post Graduate School
O&S	Operations and Support
OE	Operational Energy
OECIF	Operational Energy Capability Improvement Fund
OEPP	Operational Energy Plans and Programs
OPTEMPO	Operating Tempo
OSD	Office of the Secretary of Defense
OUSD	Office of the Under Secretary of Defense
OUSD (AT&L)	Office of the Under Secretary of Defense (Acquisition, Technology, and Logistics)
OUSD (PA&E)	Office of the Under Secretary of Defense (Program Analysis and Evaluation)
PPBE	Planning, programming, budgeting, and execution
QDR	Quadrennial Defense Report
RDT&E	Research, Development, Test and Evaluation
SECNAV	Secretary of the Navy

SECNAVINST	Secretary of the Navy Instruction
SPAWAR	Space and Naval Warfare Command
STORM	Synthetic Theater Operations Research Model
SYSCOMS	System Commands
TOC	Total Ownership Cost
U.S.C	United States Code
USMC	United States Marine Corps
USN	United States Navy
WSARA	Weapon Systems Acquisition Reform Act

Chapter 1: Introduction

The United States DoD consumes a tremendous amount of petroleum products on operations powering its portfolio of air, sea, and ground vehicles, as well as providing energy services to stationary and mobile groups of personnel. In 2013, the DoD spent an estimated $15 billion on operational energy use [1]. Operational energy is defined as:

> "The energy required for training, moving, and sustaining military forces and weapons platforms for military operations. The term includes energy used by power systems, generators, logistics assets, and weapons platforms employed by military forces during training and in the field. Operational energy does not include the energy consumed by facilities on permanent DoD installations, with the exception of installations or missions supporting military operations. Operational energy does not include the fuel consumed by non-tactical vehicles" [2].

This energy is provided almost entirely by petroleum and represents approximately 75% of total energy consumption, though this split may dramatically change during different operations or peacetime [3], [4]. This makes the DoD the single largest purchaser of petroleum fuels in the nation and world [4]–[6]. Because oil is a global commodity, total DoD spending on petroleum products is highly sensitive to volatile market prices and a multitude of other factors outside of its control. This dependence on petroleum-based fuels and price sensitivity create a significant risk to the organization, which at the very least can lead to short-term operational disruptions [7].

In addition, the monetary cost of energy is arguably the least important component of the total cost of energy for many decision makers in the DoD. Energy has several first-order impacts on the operational capabilities of any system. For example, energy consumption limits days on task for ships, range for aircraft, and self-sufficiency for ground forces between resupply. These mission-dependent energy requirements, combined with operational tempo, scope the required capabilities of their supply networks. Higher end-user energy demand necessitates larger or more frequent resupply, which exposes inherently vulnerable resupply systems to more risk of enemy interdiction and other issues. Increasing end-user capacity can displace armaments or encumber forces, limiting capabilities such as flexibility and mobility. In addition, greater energy demand, especially by the end-user, increases the resilience required in the logistics because energy shortages are quicker to occur and the consequences more significant. Most importantly, these relationships are not independent. Tactical systems that demand more energy create larger or more frequent resupply requirements that increase the probability of interdiction and consequences of energy disruption, which can only be mitigated in the short-term by delivering more energy. And all logistic systems today consume large quantities of the very resources demanded during supply. The portion consumed by the logistic chain is heavily dependent on many variables, some of which the DoD largely controls, only partially controls, or has very little impact at all. For example, the DoD can control the systems it acquires and uses but only within the limits of financial, political, and technological feasibility, which are each somewhat outside the organization’s control. In within those limits, the energy costs and capabilities of acquired and fielded systems are partially a function of an opponent’s energy costs and capabilities, which are almost entirely outside the DoD’s control.

Qualitatively, some of these risks are understood. Originally known as Fully Burdened Cost of Fuel (FBCF), the DoD created a metric in 2007 now known as Fully Burdened Cost of Energy (FBCE) to better value the “hidden” costs of energy during the acquisition process. It was legally defined in 2008 as:

> “…the commodity price for fuel plus the total cost of all personnel and assets required to move and, when necessary, protect the fuel from the point at which the fuel is received from the commercial supplier to the point of use” [8].

This metric attempts to quantify all the major costs assumed by the DoD when satisfying the future energy demands of competing systems (e.g., combat ground vehicles, support aircraft, or generators) in their potential operational environments across a range of opponents and locations. Its calculation is required at acquisition for certain programs, but its method of calculation is not standardized.

Originally, FBCE was embraced by all DoD Service Branches. Anecdotally, however, support for it has waned significantly since 2012. While regulation requirements are still satisfied, the limitations of early versions of FBCE were attributed to the concept, not application methods, and most developmental work ceased [9]. For some stakeholders, the presence of FBCE in its current form may worsen the issue of sustaining operational energy as it creates the perception that this is appropriately addressed when it is not [10]. Most recently, a concept without detailed guidance known as Energy Supportability Analysis (ESA) has replaced FBCE in some regulations though not all, exacerbating confusion [11]–[13]. Accordingly, there remains a need for a DoD-wide method that properly highlights the true cost and risks of energy dependence in acquisition decisions. This study highlights areas within the DoD’s understanding of energy that could improve or whose development has faltered. It then presents and demonstrates the use of a new metric that allows the DoD to better manage and plan for long-term energy-related costs and risk.

Chapter 2 opens the discussion with some background information on logistics and energy demand in the DoD. It gives a brief history on the development of the concept and implementation attempts along with the limitations of those attempts. While not standardized, these attempts have tended to prioritize simplicity to a level that relevance to decision makers is lost. The chapter addresses these limitations by introducing a new framework for FBCE and demonstrating its use. Through this framework, decision makers can focus on the key factors impacting energy demand and mitigate long-term costs and risk for the organization. There is a brief discussion of applicability to other organizations utilizing metrics for decision making, especially those engaged in high-risk, high-consequence, long-term forecasting with limited data. It concludes with policy implications and recommendations for future work.

Chapter 3 examines the Imperial Japanese Navy's operational decisions surrounding Guadalcanal in World War II to explore the important and inseparable connections between military capabilities and energy costs. Because of this exploration, this analysis holds significance for future military planning as it highlights the operational impacts of prioritizing short-term versus long-term logistic considerations under an organizational doctrine. Lastly, because of all those connections, this work demonstrates the challenges of creating an energy metric that is simple enough to be incorporated into decision-making processes, flexible enough to adapt to the fluid demands and constraints of operations, and complex enough to stress all the important dimensions of energy.

Chapter 4 follows the development of FBCE and the surrounding discussion in the DoD and Department of Navy. This section follows the rise and fall of FBCE as scores of organizational actions seemed to improved understanding and appreciation of energy but ultimately failed to find a way to translate that to decision makers. It is a history that simultaneously underscores the need for FBCE and the difficulty of designing and implementing it.

Building off the previous chapters, Chapter 5 continues to motivate the need for FBCE. First, it expands on the example from Chapter 3 to include uncertainty and discuss the potential value of that uncertainty to decision-making. Second, it applies the framework outlined in Chapter 2 to a new problem that more directly incorporates capability, a critical dimension of the decision tradespace for many DoD stakeholders.

Chapter 6 further expands on the complex conversation of energy in military tradespace and offers additional adjustments to that framework. These adjustments are specifically designed to deal with the issues of scoping a deeply uncertainly problem and creating a tradespace to compare system capabilities and FBCE directly. It then illustrates its use and value to decision makers with nominal present-day systems and possible future technologies. The aim is to create a metric simple enough to be quickly incorporated into decision making processes and supply initial estimates to gauge value of further refinement, flexible enough to adapt to the fluid demands and constraints of operations and planning as well as possible organization changing technologies, and complex enough to stress all the critical dimensions of energy.

The work presented is intended to inform better policies and investment decisions for military acquisitions. The discussion highlights areas within the DoD's understanding of energy that are lacking or whose development has recently faltered. The new metric discussed allows the DoD to manage and plan for long-term energy-related costs and risk better. Without an improved understanding and proper decision tools, future U.S. forces risk unsustainable energy costs and energy-related capability loss.

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Chapter 2: Rethinking Military Energy Logistics Metrics: Planning for Future Scenarios with Large Uncertainty and High Consequences

Abstract

This chapter describes the motivation behind FBCE, the limits of current implementation, and some critical relationships between energy, logistics, and capability. We then propose a new framework to incorporate energy cost and uncertainty in military decisions. This framework presents decision makers with the information necessary to mitigate long-term costs and risk for the organization that may otherwise impede future military capability. Additionally, critical considerations and lessons learned have applications to a wide range of stakeholders.

2.1 Introduction

The United States Department of Defense (DoD), consumes a tremendous amount of petroleum products on operations powering its portfolio of air, sea, and ground vehicles, as well as providing energy services to stationary and mobile groups of personnel. In 2013, the DoD spent an estimated $17 billion on operational energy use [1]. Operational energy, which is almost all provided by petroleum, represents approximately 75% of total energy consumption though this split may dramatically change during different operations or peacetime [2], [3]. This makes the DoD the single largest purchaser of petroleum fuels in the nation and world [4]. Because oil is a global commodity, total DoD spending on petroleum products is highly sensitive to volatile market prices outside of its control. This dependence on petroleum-based fuels and sensitivity to market price uncertainty create a significant risk to the organization.[1]

In addition, the monetary cost of energy is arguably the least important component of the total cost of energy for many decision makers in the DoD. Energy has several first-order impacts on the operational capabilities of any system. For example, energy consumption limits days on task for ships, range for aircraft, and self-sufficiency for ground forces between resupply. These mission-dependent energy requirements, combined with operational tempo, scope the required capabilities of their supply networks. Higher end-user energy demand necessitates larger or more frequent resupply, which exposes inherently vulnerable resupply systems to more risk of enemy interdiction and other issues. Simply increasing capacity on end-users can displace armaments or encumber forces, limiting capabilities such as flexibility and mobility. In addition, greater energy

[1] The DoD can ask for additional appropriations to cover fuel price increases. However, unexpected price rises have led to short term disruptions [44].

demand, especially by the end-user, increases the resilience required in the logistics because energy shortages are quicker to occur and the consequences more significant. Most importantly, these relationships are not independent. Tactical systems that demand more energy create larger or more frequent resupply requirements that increase the probability of interdiction and consequences of energy disruption, which can only be mitigated in the short-term by delivering more energy. Some historic examples showing the financial and capability consequences of using metrics that fail to incorporate energy in all its dimensions into decision processes or do so poorly can be found later in this chapter and in Chapter 3.

Qualitatively, these risks are understood. Originally known as Fully Burdened Cost of Fuel (FBCF), the DoD created a metric in 2007 now known as Fully Burdened Cost of Energy (FBCE) to better value these "hidden costs" during the acquisition process.[2] FBCE attempts to quantify all the major costs assumed by the DoD when satisfying the future energy demands of competing systems (e.g., combat ground vehicles, support aircraft, or generators) in their potential operational environments. Its calculation is required at acquisition for certain programs, but its method of calculation is not standardized.

Originally, FBCE was embraced by all DoD Service Branches. Anecdotally however, support for it has waned significantly since 2012. While regulation requirements are still satisfied, the limitations of early versions of FBCE were attributed to the concept, not application methods and most developmental work ceased [5]. Within the Army, attention is mostly centered on a FBCE-like tool noticeably removed from the last specific DoD guidance in 2012.

[2] Originally, this metric was known as Fully Burdened Cost of Fuel.

Additionally, some of these redesigned FBCE-like metrics are difficult to standardize across the organization and/or not intended to inform acquisition decisions. More recently, a concept without detailed guidance known as Energy Supportability Analysis (ESA) has replaced FBCE in some regulations (e.g., 2015 Joint Capabilities Integration and Development System Manual) though not all (e.g., July 2015 DoD Directive 4180.01 Energy Policy) [6]–[8]. A detailed examination of the development of this concept can be found in Chapter 4. As a result, acquisition decisions being made today do not have a formal metric that properly illustrates the consequences of the fuel demand that they create across a range of future possibilities.

Accordingly, there are two troubling current trends working in concert. First, the DoD spends a significantly larger amount on petroleum fuels relative to just a decade ago and that spending is highly sensitive to uncontrollable and uncertain market prices. This represents risk and vulnerability to the organization that could grow and ultimately undermine the effectiveness of the very force it supports in future operations. Second, the metric designed to value the total costs of fuel during the acquisition process and help alleviate the first issue has failed. Present-day acquisition decisions do not have a formal metric that properly illustrates the consequences of the fuel demand that they create. For some stakeholders, the presence of FBCE in its current form may worsen the issue as it creates the perception that this issue is appropriately addressed when it is not [9].

Creating good metrics to aid in decision making is not a task limited to the military. Across a wide range of industries in both the public and private sector, organizations rely on metrics to make decisions about risk. The relatively recent ability to collect and process large quantities of data has only increased the prevalence of such practices. However, regardless of the quantity or quality of data, every organization must face the same fundamental tradeoffs between such factors as accuracy, reliability, and ease of use when designing a new metric. In fact, the entire process from motivation through definition to implementation is fraught with competing goals and pitfalls. Properly designed metrics, highlight the crucial factors and sensitivities at a level appropriate to the decision's importance, better informing decision makers in the time available. Poorly designed metrics can easily cloud already complicated decisions through a multitude of shortcomings (e.g., focusing on unimportant factors, ignoring critical sensitivities, or being too simplistic or complicated given the scale of the decision). Decisions made based on these deficient metrics can cost organizations time, money, and, in some cases, human lives.

For example, the National Weather Service publishes uncertainty for long-term but not short-term flood stage forecasts [10]. This was a conscious choice by the organization because forecasted uncertainty for average flood cycles tends to diminish to insignificance as a flood approaches. However, this practice fails to account for the risk and consequence of extreme events. In 1997, the weather service predicted the Red River in North Dakota would crest at 15 meters. Sadly, the river peaked at over 16 meters, slightly above the planned barricades and caused over $1 billion in damages [11]. Local governments may have prepared differently had the National Weather Service communicated the uncertainty in their forecast.

This chapter makes a contribution to the literature by outlining a new framework for FBCE to better handle the inherent uncertainties and nonlinearities of future fuel demand and risk and their connection to logistic burden. If implemented, this new metric creates the opportunity for the DoD to manage and plan for long-term costs and risk better. Critical considerations and lessons learned have applications to any organization utilizing metrics for decision making, especially those engaged in high-risk, high-consequence, long-term forecasting with limited data.

This chapter is organized as follows. Section 2 and Section 3 provide background on military logistics and energy demand, respectively. Section 4 outlines the history of FBCE. Section 5 outlines the most accepted method of FBCE calculation, highlights its value and limitations, and identifies previous attempts to extend it. Section 6 provides evidence to support the claims that incorporating uncertainty and nonlinearities are fundamental to understand the quantity and cost of future energy demand better. Sections 7 and 8 establish and discuss methods to expand the existing FBCE framework. Section 9 concludes the analysis, recognizes policy implications, and identifies areas of future work.

2.2 Background

Current fuel use is not merely a function of what is consumed by combat forces. Fuel must be moved from points of sale to end-users, which can require complex, military-owned logistic webs that consume fuel themselves.[3] One report estimates that 70% of total Army logistic tonnage is fuel, while another found fuel to represent about 50% of average convoy load by volume [12], [13].[4] The costs and risk to acquire, staff, and operate these chains are not encapsulated in the reported fuel cost figures and represent additional and ambiguous costs absorbed by the organization [14]–[17].

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[3] It is estimated that around one-half of all DoD personnel and one-third of the total budget are dedicated to logistics [4].

[4] Including water and fuel, different reports estimate 70-80% of ground logistics and 90% of naval logistics [17], [80], [99].

For some operations the monetary, non-monetary, and opportunity costs of potentially vulnerable logistic chains may represent the most significant expenses associated with combat-system fuel demand. Properly planning for such future operations requires not only consideration of the potentially higher costs but also the added uncertainty, which can be very large [18].

The heavy costs of logistics and the risk of shortfall are not creations of modern warfare. History is full of examples of otherwise capable military forces halted by logistic support that became insufficient in certain environments and operations. Napolean's Grande Armeé entered Russia in 1812 with over 500,000 men and left with only 20,000 [19]. While the Russian weather and soldiers were major contributors to this, "they did so by exacerbating a monumental underlying problem: poor logistical planning on the part of Emperor Napoleon Bonaparte" [19]. As supply lines lengthened, poor logistic planning forced Napoleon's soldiers to choose between the sustainment (i.e., food) and military value of horses.

> "The consumption of horses may have temporarily staved off starvation for the men, yet it had disastrous ramifications for the military success of the campaign. As horses died, the size and effectiveness of the French cavalry dwindled, as did the ability to transport supplies in whatever wagons remained" [19].

Van Creveld hypothesizes that a similar issue happened to Rommel in North Africa in World War II [20]. Across all operations, Rommel's extended logistic lines consumed 30% to 50% of all the fuel that landed in North Africa and this varied considerably based on-the-ground logistic length, as recreated below in Figure 2.1 [20]–[22]. Estimated logistic burden soared whenever Rommel advanced and contracted when he retreated. Rommel's attempts to use newly captured ports for logistics took time to reopen, increased the losses of Italian shippers from Malta-based Allied aircraft, and increased the risk of RAF port attacks based around Alexandria. During the winter of 1941, the fuel shipments became so critical that the Axis had "100,000 tons of warships being used to protect 20,000 tons of merchant shipping [in the Mediterranean], and the cost in fuel became prohibitive" [20]. These kinks in the logistic pipeline directly impacted the size and tempo of operations supportable in North Africa.

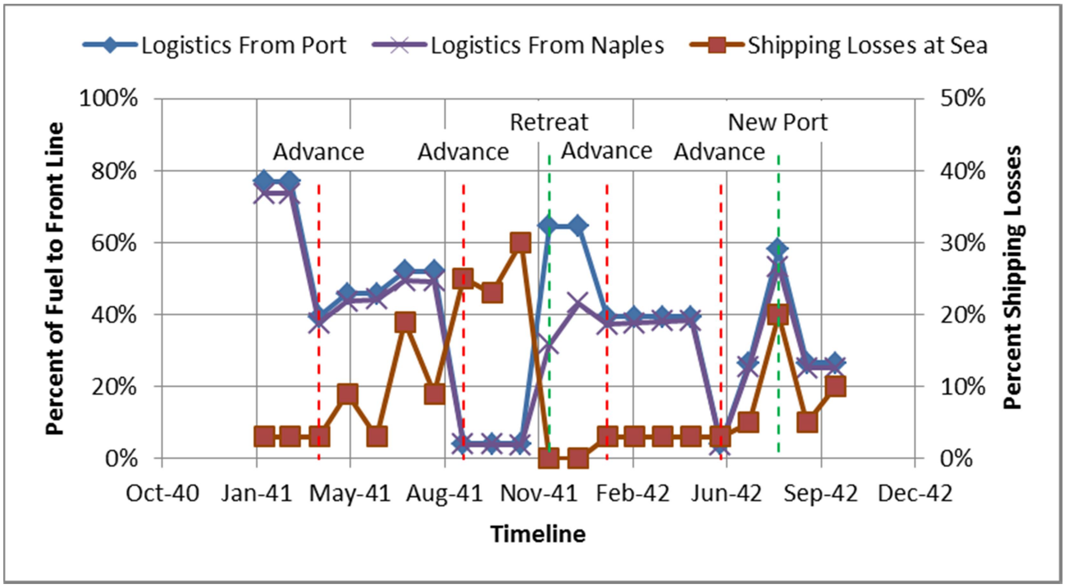

Figure 2.1: Rommel's Logistic Burden. Data from [14]–[16]

This example demonstrates the inherent connections between military capability, logistics, and energy. Rommel was an infamous tactician. In certain environments against certain opponents, his blindness to energy and logistic issues was inconsequential. However, the vast expanses of rugged terrain in northern Africa plagued this oversight. The rate and distances of energy demanded by his advances pushed ground logistics into ruin. During advances, the heat and terrain incapacitated 30-50% of logistic vehicles, which were already in short supply [20]. Those that survived burned more during transport than they were able to deliver. Advances tended to grind to a halt under the weight of their own logistic burden.

Importantly, Rommel's apparent inability to appreciate the nonlinear impacts of such factors as distance on logistics and its connection to operational capability had organizational consequences. From the beginning, he demanded a force that exceeded sustainable estimates made earlier by German engineers and scouts. This not only came at the detriment of German armies in Europe, but was one of the primary factors that hindered the operation. If the tactics and forces most likely to succeed required unsupportable logistics, plans should have been re-evaluated. If the capability possible, given logistic constraints and the impact of location dependent factors, was not likely to achieve victory, Rommel should never have ventured from Tripoli. By perceiving the limitations of his logistic means and staying at Tripoli, Rommel would have needed far fewer forces, dramatically reducing his logistic demands, strengthening his foothold in Northern Africa while reducing his impact on European efforts. Whether perception of these relationships would have changed Rommel's decision to seek a larger force and then disobey orders and advance can only be conjecture. However, the results of the path he chose are not. His lack of appreciation for the impact of logistics in Northern Africa prevented him from seeing what the campaign ultimately became, a battle of attrition Germany couldn't support. His multiple advances consumed large quantities of valuable resources, generated little capability, and had little chance of campaign success. Perception of this issue in hindsight is relatively easy compared to the challenge of recognizing its possibility in potential future operations or even its existence in ongoing operations. Chapter 3 presents a deeper exploration of another example intended to highlight the difficulty of exposing vulnerabilities created by the connections of energy, logistics, and capability.

The modern US military is by no means immune from this connection between combat force capability and logistic supply. Since WWII, the capabilities of the modern US military have grown immensely along with the logistic tail and the consequences of shortfall. Petroleum consumption quantity has grown considerably as have the specifications of refining.

Additionally, many modern systems have components that wear out quickly, especially in certain environments (e.g., dusty and arid climates), can only be manufactured by certain companies, and have to be transported around the world. An infamous recent example involves the Air Force and Marine Corps Osprey. Based on public news sources and social media, the smaller fan stages of aircraft's engines are very sensitive to sand and dust with early versions of the $1.2 million engines requiring maintenance or replacement after only 50-100 flight hours. While currently unsubstantiated by official sources, the Marine Corps did release new guidance for Osprey pilots after a training flight mishap over a dusty landing zone resulted in the deaths of two Marines aboard [23]. Additionally, the Air Force has invested in binding agent to be sprayed on training landing zones to reduce the amount of dust and sand that is stirred up [24]. Despite the potential of certain systems such as smart munitions and nuclear powered ships to decrease it, the logistic demands of the modern US military have grown in complexity and size. It has been argued that U.S. forces in Operation Desert Storm outpaced their supply lines [25]–[27]. More recently, there were the enormous challenges of supporting two concurrent conflicts with extended logistic lines in Iraq and Afghanistan. Despite the disparity in military might, many of these logistic chains were vulnerable. A report estimates one casualty was incurred for every 38 fuel resupply convoys in Iraq and every 24 in Afghanistan, where around 14 and 2.5 convoys were conducted per day, respectively [13].[5] The same work estimates that historically about 10%–12% of Army casualties can be attributed to resupply. Therefore, when planning for future scenarios, there needs to be careful consideration of the connection between logistics and capabilities, especially given the potential of certain technologies to fundamentally change logistics, military

[5] Another reported estimated one Marine casualty was incurred for every 50 convoys in Afghanistan [99].

capabilities, and the relationships between (e.g., unmanned combat and logistic systems and direct energy weapons). Otherwise, in addition to uncertain and sometimes large energy costs, there is a real risk that logistic challenges will severely impede the capabilities of future U.S. forces.

2.3 Energy Demand

The Defense Logistics Agency-Energy (DLA-E) purchases fuel for the DoD. DLA-E uses fixed-price contracts with specified contingencies written in to allow price adjustments. Typically, these are one-year contracts, though some may be awarded as multi-year under the Federal Acquisition Regulation (e.g., supplies and related services). These contracts tend to be awarded based on the lowest cost to a specified location. However, they fail to account for the costs of any necessary DoD logistics to move the fuel to its final destination [28]. Some additional limitations of this fuel purchasing structure are discussed in Chapter 6.

The variability of activities in the Afghanistan and Iraq wars as well as oil price fluctuations have contributed to changes in annual DoD outlays for petroleum products. Inflation-adjusted purchase data are displayed in Figure 2.2 [1], [29]–[43]. The majority of purchase data comes from DLA-E reports [1].[6]

[6] DLA-E was known as the Defense Energy Support Center before 2010.

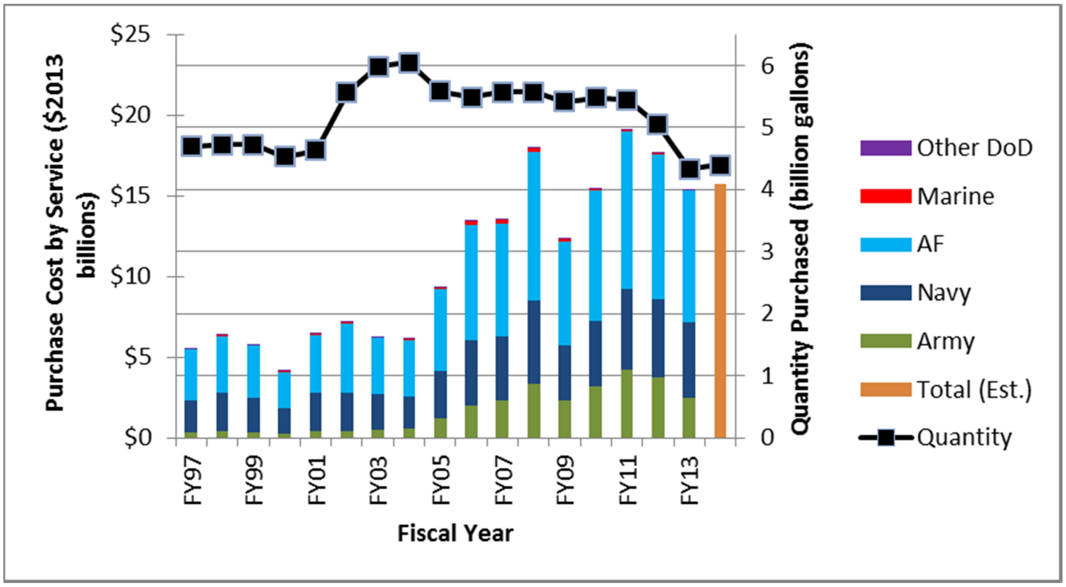

Figure 2.2: DoD Annual Adjusted Cost and Quantity of Petroleum Products Purchased. Data from [1], [29]–[43]

As shown, adjusted annual spending remains near recent highs despite quantity purchased falling to its lowest levels across this time frame.[7,8] This suggests that fuel expenditures are much more sensitive to uncontrollable market prices than controllable organizational demand, creating challenges for planning and the risk of budget shortfalls that can impact operations [44]. This sensitivity and the risk it creates are discussed in more detail in Chapter 6 and Appendix A.

Other studies have linked advances in modern warfare to increased fossil fuel usage per soldier/sailor/airmen/marine, finding a 175% increase since Vietnam, growing from 8 gallons per troop per day in 1970 to 22 in 2007, at an average annual increase of 2.6% over the last 40 years [45]. While troubling, properly appreciating the implications of this and other similar analysis is difficult given significant organizational shifts in the DoD, where total fuel use has gone down but been outpaced by force size reductions. Across a wider horizon, quantity of fuel purchased

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[7] The fuel estimate for FY14 came from an Operational Energy Annual Report [1]. Historically, these tend to underestimate purchase quantity and cost relative to DLA-E publications.
[8] Additionally, both the percent of outlays on fuel and the uncertainty in that quantity grow over this time period.

by the DoD is at or near all-time lows dating back to before the Vietnam War, but both the amount and percent of the DoD budget spent on that fuel remains near recent all-time highs.

There is additional reason to justify concern caused by petroleum price uncertainty. Significant portions of the world oil supply travel through various geographical choke points (e.g., the Strait of Hormuz and the Strait of Malacca) [12], [46]–[49]. Domestic or international instability in these areas can significantly affect the market risk, observable through such metrics as futures contracts and insurance rates [50]. Increases in insurance premiums to transport ships transiting these areas can significantly impact market prices. Figure 2.3 shows the crude oil spot price free on board (FOB) for two locations [51]. As seen in the figure, insurance rate increases in response to Iranian mining of the Persian Gulf may be partially responsible for the 2-3 fold market oil price spike in 1991 [52]. Also as shown, these price increases occurred at the very time the U.S. and coalition forces were ramping up for the Persian Gulf War. The acute demand caused by such military operations can be very significant. For example, General Schwarzkopf's five-day maneuver used an estimated 30% of the 8-10 billion gallons of fuel consumed by the DoD in all of FY1991 [53]. In other words, the military was ordered to act at the very time risk and market prices increased. Budgeting for even the unburdened energy costs of such an operation based on a low-risk market would have dramatically underestimated the actual costs. Forecasting burdened energy costs needs to account for such possible relationships when contemplating future scenarios.

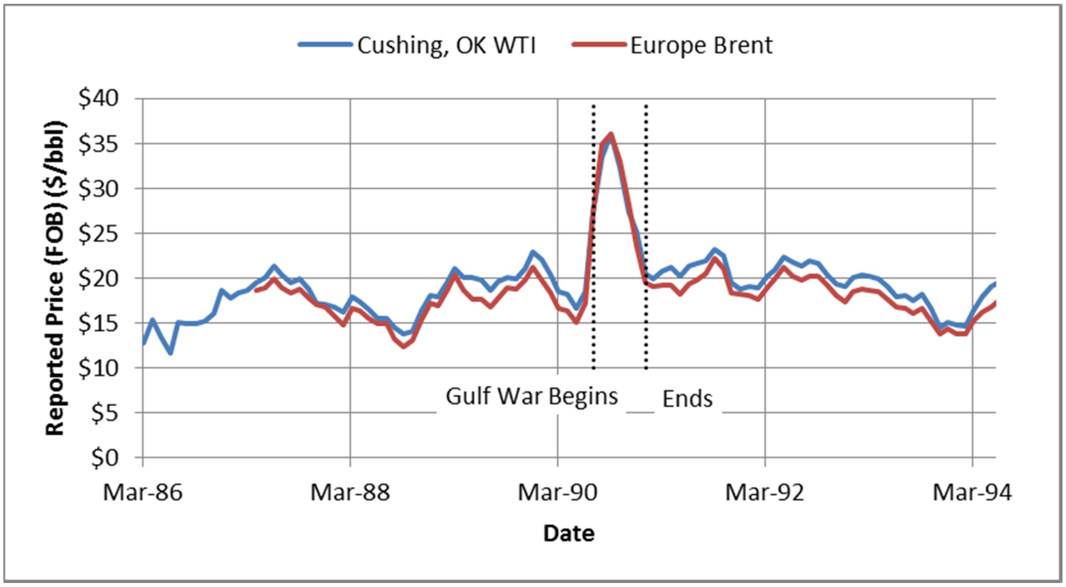

Figure 2.3: Spot Price for Crude Oil.
Note: FOB is Free On Board; WTI is West Texas Intermediate

2.4 History of FBCE

This section summarizes the development of FBCE. Chapter 4 contains a more detailed history. The need for a metric focused on energy-related costs and risk was first identified in a 1999 Defense Science Board (DSB) memorandum commissioned by the Office of the Under Secretary of Defense for Acquisition, Technology and Logistics (AT&L) [54]. Following that memorandum, several reports emerged stressing the critical importance of finding a way to incorporate a system's logistic footprint into the acquisition process. A 2001 DSB report stated that "the task force found that these benefits [of energy efficiency], and the burden to warfighting capability of not focusing on efficiency, were not factored into decision-making." A report by the JASON defense advisory group remarked that

> "[f]uel use is characterized by large multipliers and co-factors...it takes fuel to deliver fuel….[It] imposes large logistical burdens, operational constraints and liabilities and vulnerabilities: otherwise capable offensive forces can be countered by attacking more-vulnerable logistical-supply chains" [55].

Finally, a report by Crowley et al. in 2007 identified major areas of disconnect between the DoD's current energy consumption practices and its energy strategy [56]. The report recommended bridging the fiscal disconnect, in part, by "incorporate[ing] energy considerations (energy use and energy logistics support requirements) in the department's key corporate processes", including acquisition [56].

In the middle of 2007, two offices within the DoD tried to establish such a metric. In April, AT&L released a memorandum that established three pilot programs [57]. A few months later, another DoD office released a memorandum that created a rudimentary methodology for a metric named Fully Burdened Cost of Fuel (FBCF) [58].

By 2008, the National Defense Authorization Act mandated the calculation of FBCF. Section 332, paragraph (g) of this act defined it as

> "…the commodity price for fuel plus the total cost of all personnel and assets required to move and, when necessary, protect the fuel from the point at which the fuel is received from the commercial supplier to the point of use" [59].

For several years additional guidance and regulations were passed advancing FBCE [3], [17], [60]–[64]. This culminated in 2012 when AT&L issued its most recent guidance on FBCE methodology to inform trade decisions during acquisition. It was also designed to provide consistency between service calculations, which still varied widely [65]. The guidance specified that unlike other cost methods, FBCE is intended to be both scenario-dependent and account for apportioned delivery and protection costs [66]. FBCE was expected to "over time help DoD manage larger enterprise risks" [67].

2.5 Implementation of FBCE

While the details of calculation differ significantly, Figure 2.4 summarizes the accepted process to calculate FBCE. The general steps are on the left-hand side with more specific recommendations illustrated in the center [65]. Fuel originates at the point of sale and is sold at the per-gallon "base cost" of fuel. Then, the per-gallon costs of a military-owned logistic chain are calculated and referred to as "additional logistic cost". Summing these two costs determines the assured delivery price (ADP) ($/gallon). Finally, the FBCE is calculated by multiplying the daily system demand by the ADP. Assuming point values results in a deterministic calculation for ADP and FBCE; including uncertainties results in distributions. As these details are not regulated, different calculation methods exist.

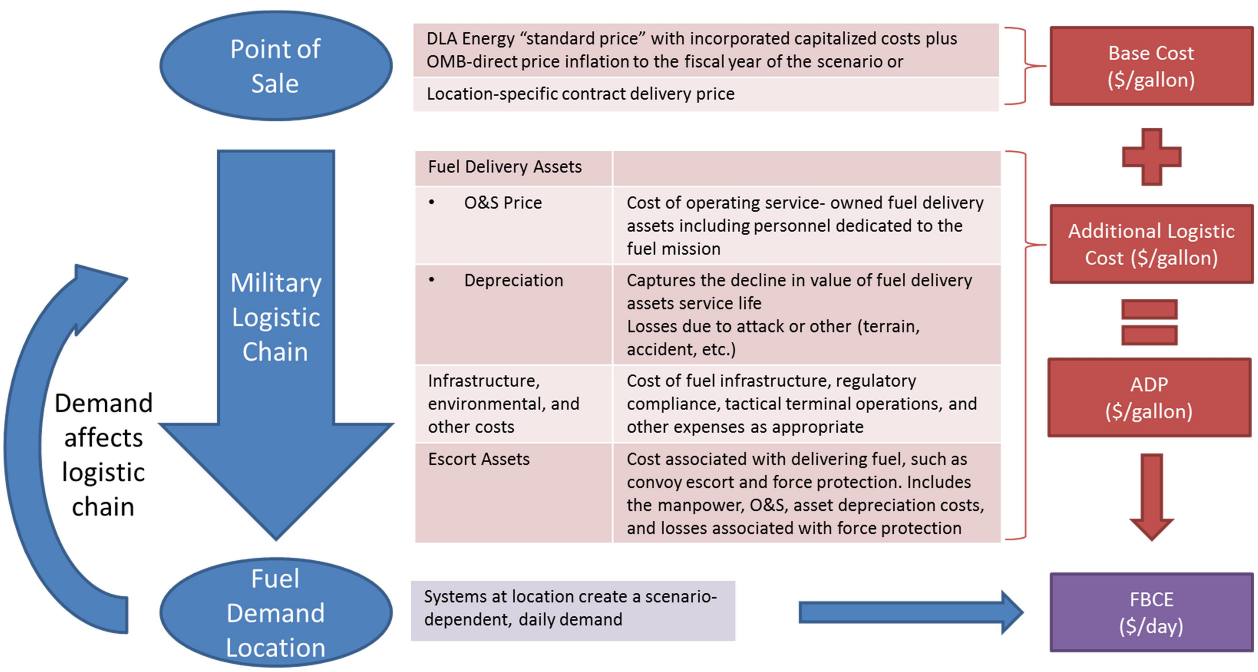

Figure 2.4: FBCE Cost Elements and Calculation Framework

Simplifying the previous figure, Figure 2.5 illustrates some of the critical components of FBCE. Combat weapon systems create fuel demand that requires the establishment of logistic chains, some portion of which may need to be protected by escorts. During delivery, there is a risk of losing logistic and/or escort assets to mechanical problems, environmental factors, and enemy actions. Additionally, both the logistic and escort assets consume fuel and incur some depreciation or use cost. Normally, this includes a percent allocation of the acquisition cost but could be expanded to include such items as the salary costs of drivers and mechanics or the opportunity cost of using combat systems for escort purposes rather than offensive combat operations. As explained below, work on FBCE up to this point has focused on certain aspects of Figure 2.5, while excluding or subjugating others. Because the importance of modeling each component or incorporating uncertainty and correlations between components (e.g., operational value of escorts and mechanical and interdiction loss rates) can vary by scenario, this can dramatically affect the metric.

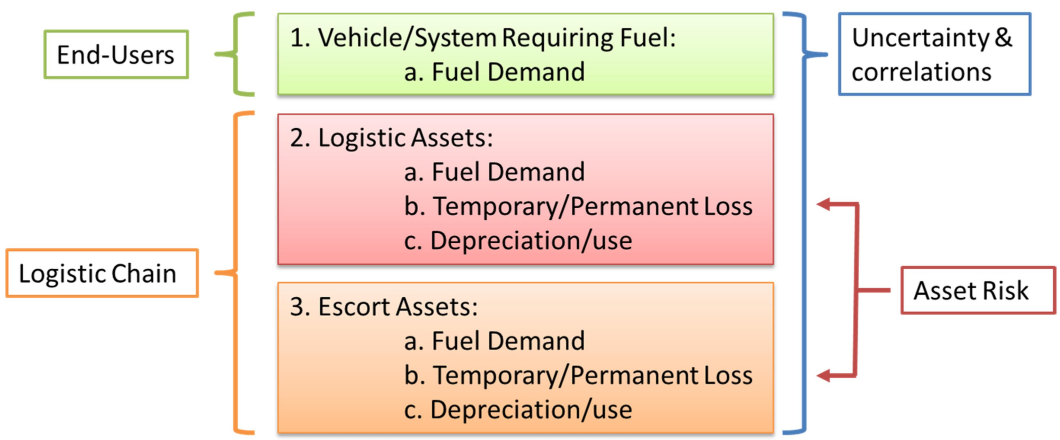

Figure 2.5: Critical Components of FBCE

2.5.1 Common FBCE Method

Most FBCE methods assume a single wartime scenario, independent of the analyzed system's demand. These scenarios tend to assume a single supply location, demand location, and deterministic parameters [68], [69]. Many of these models ignore potentially significant costs and assume a standard fuel price. Additionally, baseline models ignore the feedback loop shown in Figure 2.4, meaning the logistic chain, ADP, and risks are independent of fuel demand. In general, these limitations suggest that the current implementation of FBCE prioritizes simplicity to such an extent that important insights are lost and the metric's relevance eliminated.

As implemented, this method establishes a framework to build on. While not intended for direct comparison, it also establishes a point estimate potentially useful to the decision maker and satisfies the regulatory requirement to calculate FBCE.[9]

However, there are several evident limitations. First, assuming a standard fuel price systematically underestimates fuel cost at remote locations, where FBCE is likely to be higher and more important to understand [70]. Second, logistic assets, especially escort assets, are high-value systems the loss of which may significantly impact overall costs. Additionally, missing nonmonetary costs can also be significant as these can include a normative evaluation of the value of the human resources invested or greenhouse gasses emitted [13], [71].

Next, most methods are deterministic. This ignores the inherent uncertainty involved in every step of the FBCE calculation. Additionally, without some scenario breadth, there is no way for decision makers to understand the significance of calculated FBCE differences even if they are numerically large. Several key lessons need to be kept in mind. Model runs based on average values can be very misleading especially for distributions with significant tails and no one single deterministic scenario will ever actually happen [72]. Accordingly, military planners need to consider the entire distribution of FBCE to understand the significance of relatively rare events and think through and plan for contingencies.

[9] Using publicly available guidance and notional scenario, the cited model generates an ADP of less than $6 [68]. Other model estimates for various scenarios have generated results ranging from $3 to $400 per gallon [71], [100].

Finally, as a result of deterministic inputs, the method is unable to model any correlation between parameters. For example, having longer delivery routes will increase maintenance costs of support vehicles and allocating escort assets to fuel delivery will decrease the rate of enemy interdiction. While data are limited, correlations can be evaluated parametrically and sensitive ones can be refined through such methods as enhanced modeling and expert elicitation [73].

2.5.2 Other FBCE Methods

Last updated in 2011, AT&L developed a FBCE calculator that uses Monte Carlo simulation to characterize the distribution of FBCE. At one point, the Navy and Marine Corps based their FBCE development on this model, and several theses were published analyzing specific systems [74]–[76]. This methodology, which began the important exploration of incorporating uncertainty, is no longer used.

The Army's current work on FBCE is led by the Logistics Innovation Agency [13], [71], [77]. Their work has resulted in a bottom-up microeconomic model that uses available data from DoD databases to generate deterministic costs to support tradeoff analysis. Generated values include many monetary and non-monetary costs. While not calculated directly, later versions of this model do account for the consumption of resources by the logistic chain (i.e., the fuel multiplier effect) [78].

While one of the most complete models developed up to this point, it still has limitations that hinder its ability to fulfill the task assigned to FBCE. First, it relies on existing data, mostly from Iraq and Afghanistan, which may not properly capture the range of costs across possible future operations. Would acquisition decisions made for Iraq and Afghanistan have been appropriate if they were based on data from the Bosnian War?[10] Next, it is difficult to extend the model from examining current logistic scenarios with fielded systems to analyzing the range of possible logistic scenarios needed to support future operations. Lastly, cost estimates are generated deterministically and are unable to quantify uncertainty or directly explore the consequence of risk.

After some initial work examining AT&L's method, NPS has published several works arguing for and demonstrating the use of Input-Output modeling, common in Life Cycle Assessment, to generate FBCE-like metrics [25], [70], [78]–[82]. Their analysis began with developing an understanding of what they termed the "fuel multiplier effect" or the exponential growth of fuel demand by the logistic chain during multi-stage logistic chains. This work was expanded to analyze other resources. The modeling generates multipliers that represent the number of units of input needed for one unit of demanded output.

NPS has found that these exponentially growing multipliers are very scenario dependent (e.g., length of supply chains, terrain, infrastructure, and escort requirements). They also recognize that the "[t]he Navy has counted on uncontested supply lines for decades" [25]. If that changed, historic data do not properly reflect the substantial additional costs that could occur [78]. Though simpler than LIA's, this model is still data driven and does not attempt to directly address the uncertainty across a range of future scenarios.

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[10] In the beginning of this conflict, rapidly changing logistic needs increased requirements (e.g., geography and poor ground conditions), which was found to be a primary driver for cost overages [101].

2.6 Uncertainty and Nonlinearities

In general, current modeling of FBCE and similar metrics has focused on analyzing it in single, “representative”, system-independent scenario. In many of these scenarios, uncertainty is low and nonlinear relationships between end-user demand and logistic burden are not critical. While representing what current modelers believe to be a probable future, they fail to show the significance of system-demand dependent and/or high-risk scenarios [72]. Given the correlation between military involvement and risk and/or the significant consequences of improper preparation, there is an argument that FBCE calculations and acquisition decision makers should focus on or at least consider these higher risk scenarios [83], [84].

Because of FBCE’s dependency on geographic location, clearly there are scenarios where logistic energy costs are more significant than others. From domestic locations or similarly stable supply points, distances between supply and demand are short, local infrastructure and energy sources are reliable, and the risk of enemy attack is extremely low. Total energy costs for these operations may be large but certain and dominated by the consumption of the energy-demanding combat forces. For example, long-range bomber operations can and commonly are supported from stateside bases. Overseas missions supported by such assets consume large quantities of fuel but the portion consumed by logistics is small. Additionally, military logistic chains are short, infrastructure is reliable and of relatively high quality, and both are extremely unlikely to be attacked. Accordingly, uncertainty and risk are low.

The situation changes when combat forces are deployed. Deployment is necessary due to system capability limitations, mission requirements, and/or operational tempo. It may even be desired as forward deployment can positively impact factors such as response time and combat system resource consumption per mission [85]. Deploying combat forces usually requires extending logistic lines and allocating escort assets. For many reasons (e.g., large distances, difficult topography/terrain, and enemy interdiction), this can significantly change the total fuel consumed per mission, the proportion of that total consumed by logistics, and dramatically increase the uncertainty involved in the calculation of either. Critically, properly planning for such operations requires not only consideration of the potentially higher costs but also the added uncertainty, which can be very large. Next, we address some of these aspects in more detail. Incorporating these relationships becomes more important as risk grows.

Allocating escort assets to logistic chains creates the possibility of sustaining losses. Traditionally, these assets represent high-value, high-fuel consumption systems. Using them to protect fuel convoys can significantly increase the portion of resources consumed in delivery, represents an opportunity cost as they become unavailable for other missions, and exposes them to infrequent but consequential loss.

Per unit energy costs and quantity of energy demand are interdependent. Accordingly, changing end-user fuel demand should have nonlinear effects on fuel delivery costs (e.g., step functions for new equipment and assumption of more risk to satisfy increasing demand). In the short term, if the current personnel and equipment supporting fuel delivery is near capacity, only small increases in demand will be able to be satisfied (e.g., additional trucks and drivers are not available). Pushing towards capacity might require foregoing preventative maintenance, safer but longer routes and the support of escort assets. Each of these would in turn increase the per gallon price of fuel, as the probability of mechanical failure and enemy interdiction increased. In the long term, significant increases in fuel demand would require the acquisition and transport to theater of more fuel-delivery support assets, such as fuel trucks. Not only do they consume fuel themselves, but more fuel trucks require more trained operators and maintainers. These new personnel in turn need logistical support, such as food and water, which take fuel to deliver. Accordingly, total fuel demand should influence both the magnitude of fuel required and the per gallon cost. As such, reducing demand might also allow the fuel delivery assets to undergo more preventative maintenance, increasing their availability and/or reducing the probability of mechanical failure. Therefore, improving end-user system efficiency (i.e., reducing demand) can have cascading impacts on both the expected cost of that fuel demand and its amount of uncertainty.

The importance of uncertainty also grows with longer logistic chains and higher risk. For example, while a “normal” fuel delivery to a location might take two days, issues related to weather, enemy action or mechanical failure could significantly increase this for any particular delivery. The distribution of delivery times is very likely proportional to average delivery time. As logistic lines become longer, so does the spread of possible times that need to be considered. Large uncertainty can dramatically alter plans as at least contingent strategies need to account for the tails of these distributions (i.e., size or frequency of supply convoys or increase storage capacity at the end-user location), which increase the cost and uncertainty of energy demand.

When estimating the value of end-user system efficiency, FBCE modeling needs to account for these relationships. For the military, the value of future efficiency may be in its effect on expected cost, spread, or some combination of many descriptive statistics.

Figure 2.6 shows the mean and median cost of fuel delivery in dollars per gallon for a Monte Carlo simulation of a simplified logistic chain. This simulation is merely a two-stage chain with aircraft delivering fuel to truck convoys that then deliver it to end-users. Using publically available data, the only cost represented is the proper allocation of acquisition cost as a function of demand and assumed logistic system capacity [86]–[90]. Operating costs and the fuel multiplier effect are excluded. The error bars show the interquartile range. A stage's size is a function of fuel demand given assumed capacity. The probability of attack is assumed to increase with stage size. Incorporating escort assets can partially offset this growth but creates the possibility of losing these assets. Given an attack, there is a small probability of asset loss that also grows with convoy size. Larger convoys also increase the probability of suffering multiple losses if an attack results in a loss.

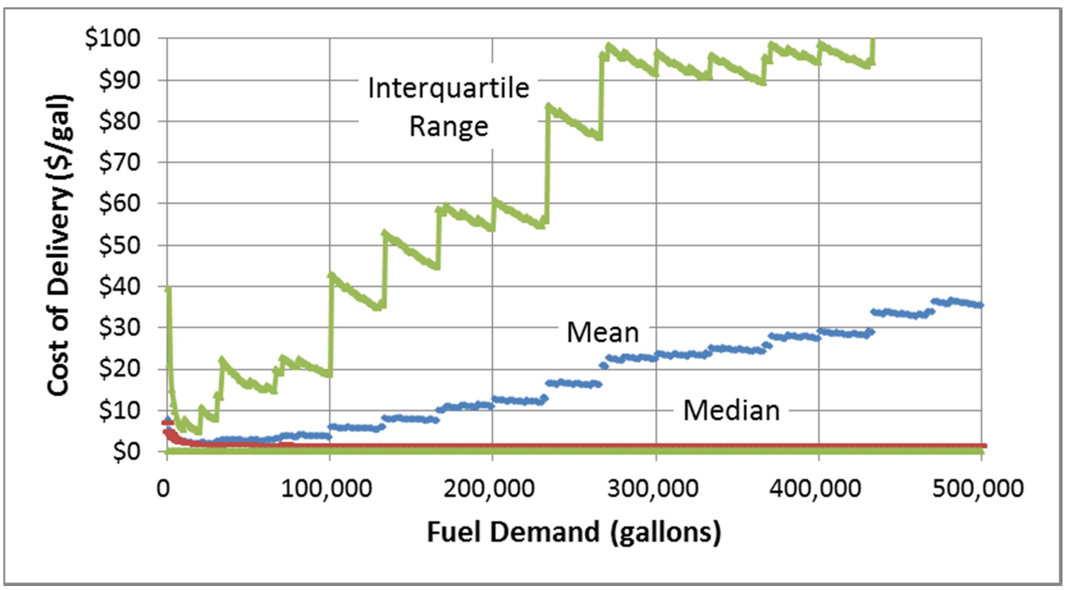

Figure 2.6: Growing Mean and Interquartile Range of Fuel Delivery Cost

As shown, the mean and median cost of delivery diverge and uncertainty quickly grows. Also incorporating the cost step functions of new systems is minimally important in the median cost of delivery but very pronounced in the interquartile range. Even within this simplified simulation, the value of efficiency for an acquisition decision maker may be rooted in the reduction of expected cost and/or uncertainty.

2.7 Reframing the Problem

Properly demonstrating the consequences of future energy demand across a range of possible scenarios requires a new framework. This framework would incorporate uncertainty and directly assess risk as a dimension of the solution space and more appropriately represent the range of operations the military must prepare to face. This more complicated framework is not necessary for low-risk, low-demand scenarios where uncertainty is small and linear relationships are reasonable approximations. However, as argued, the importance of such a framework grows dramatically with risk and demand. At the same time, the consequences of using linear approximations for these types of problems grow at an equivalent rate.

This sort of framework creates the opportunity to compare within and between scenarios. Given a single scenario, the logistic cost and uncertainty of two competing systems with similar capabilities could be directly compared. Given significantly differing effectiveness, the amount of uncertainty or cost necessary to overcome other capability gaps could be assessed, in some sense similar to the expected value of perfect information (EVPI) from decision analysis.

This research gives a normative example of Rommel's forces in North Africa for an assumed front line to the east of Tobruk [20]–[22]. In this example, the impact of the distribution port is analyzed as the rest of the scenario and end-user demand is held constant. Tripoli was the farthest port from the front line, which resulted in large logistic fuel consumption during delivery but created the smallest risk to logistic assets from British forces. Tobruk was the closest, which reduced the logistic burden but increased risk. Benghazi was in between. FBCE ratio is plotted across low to high fuel demand and risk. FBCE ratio is similar in concept to the fuel multiplier effect but accounts for other previously discussed nonlinear relationships. For this initial discussion, depreciation and use costs, as shown in Figure 2.5, are ignored. Simplistically, FBCE ratio is merely input over output or:

$$FBCE\ Ratio\ (D,R) = \frac{Demand_{EndUser} +\ [Logistic\ Burden]}{Demand_{EndUser}}$$

$$= \frac{Demand_{EndUser} + \left[\{Burden\}_{Logistic\ Asset} + (Burden)_{Force\ Protection\ Asset}\ \right]}{Demand_{EndUser}}$$

$$= \frac{Demand_{EndUser} + \left[\{Demand + Risk\}_{Logistic\ Asset} + (Demand + Risk)_{Force\ Protection\ Asset}\ \right]}{Demand_{EndUser}}$$

More specifically, it is defined as

$$FBCE\ Ratio(D,R) = \frac{\boldsymbol{n_e g_e}\alpha_1 + \left[\{\boldsymbol{n_L g_L}\alpha_2 + \boldsymbol{c_L}\alpha_3\}s_i + \left(\boldsymbol{n_f g_f}p\alpha_4 + \boldsymbol{c_f}\alpha_5\right)s_i\right]}{\boldsymbol{n_e g_e}\alpha_1} \qquad \textbf{2.1}$$

where D is fuel demand, R is risk, n_e is the number of end-users in the scenario, g_e is the consumption of those assets per combat mission, α_x is a conversion factor that transforms the quantity to dollars at location *x*'s appropriately burdened fuel rate, n_L is the number of logistic assets not impacted by random loss events (e.g., enemy attack or mechanical failure), g_L is the consumption of those assets per unit distance, c_L is the number of logistic assets impacted by random loss events, s_i represents the impact of scenario *i* on the other logistic factors, n_f is the number of escort assets not impacted by random loss events, g_f is the consumption of those assets per unit distance, *p* is the proportion escort is allocated, and c_f is the number of escort assets impacted by random loss events. Bolded variables represent distributions that are functions of expected demand and risk and impacted by their uncertainty. Through this equation, risk free scenarios with insignificant logistic demand, create a FBCE Ratio of one across all end-user demand. Additionally, systems with zero end-user demand result in an undefined FBCE Ratio across all levels of risk, which by convention is also defined as one.

Fuel demand is the total end-user fuel demand as defined by the combat scenario. Risk is a measure of the location-dependent exposure to temporary and permanent loss from such factors as mechanical failure, environment factors, and enemy action. The quantity of fuel demand and risk both impact the expected FBCE ratio and its amount of uncertainty. As a consequence of such issues as subjective and objective randomness, there is significant uncertainty in almost all of these terms. Additionally, there is also correlation between the terms and uncertainty. Not all of these terms, their assumed level of uncertainty, and assumed correlations are necessary for every scenario. Simplifications can be tailored to a level appropriate for particular decisions or scenarios. In other words, there is a hierarchy of analysis so that answers to questions are found with minimal quantification and detail. For example, some scenarios may not require escort so those applicable terms, the associated uncertainty, and correlations can be eliminated.

For Rommel, the ports are approximately equally spaced geographically. However, the marginal changes to fuel demand are not given the nonlinear increases in consumption and uncertainty of that consumption from the logistic assets as length of delivery increases. In a similar sense, the marginal impact to risk is nonlinear. Using ports closer to the front line creates longer sea supply lanes, which increased exposure to ships from British forces. Additionally, the ports themselves were more open to attack. The summation of which nonlinearly impacted the expected risk and uncertainty of that risk.

In Figure 2.7, the three port locations are mapped in the FBCE Ratio solution space. For this example, the intermediate mappings, from Italian to African port and then from African port to the front line, have been combined. Point locations represent the expected mean FBCE Ratio. The circles surrounding each represent the standard deviation used to denote the relative levels of uncertainty. All locations have similar levels of risk and fuel demand correlation. As seen, Benghazi has the lowest expected FBCE Ratio. Given the sensitivity of FBCE Ratio to risk, Tripoli and Benghazi has similar standard deviations but different covariance factors. Tobruk, with its large assumption of risk, has the highest FBCE Ratio standard deviation. These relationships are more readily apparent when comparing the CDFs.

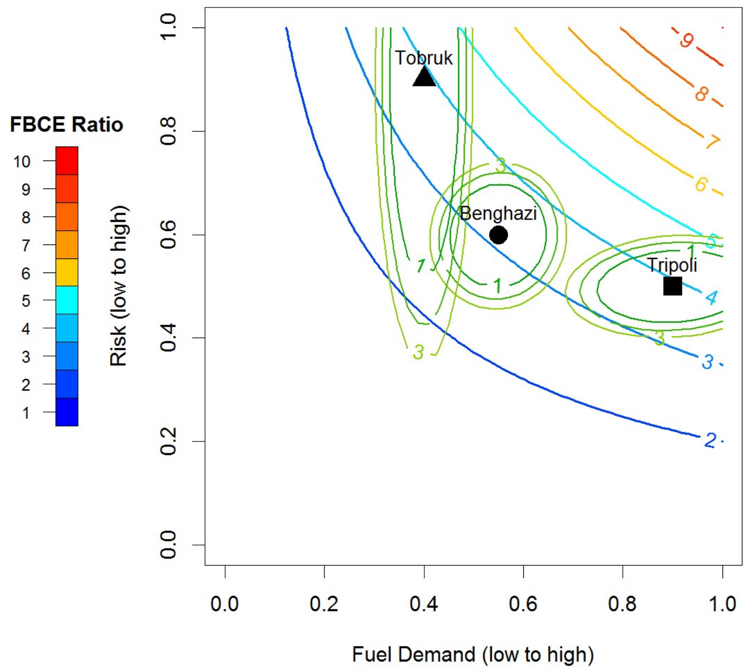

Figure 2.7: Hypothetical FBCE Ratio Solution Space for Rommel's Forces in North Africa

Figure 2.8 shows the CDFs for these three locations assuming log normal distributions. As shown, the FBCE Ratio background contours are non-linear across both axes, with greater sensitivity to Risk. There are two important points to note. First, Benghazi, which is closer than Tripoli, requires the assumption of slightly more risk to significantly reduce fuel demand. Given the shape of that solution space, this results in a noticeable decrease in the FBCE ratio mean. However, since the uncertainty of the FBCE ratio is assumed to be so sensitive to risk, both locations create a distribution with similar standard deviations. Accordingly, Benghazi stochastically dominates Tripoli. Second, because of its proximity to enemy forces, Tobruk further reduces fuel demand but less than that previously seen and requires the assumption of significantly more risk. Because of the previously mentioned relationships, the impact to its CDF's standard deviation is much more pronounced. As seen, there is portion of Tobruk's distribution with a lower FBCE ratio than Benghazi. However, because of the risk involved, the distribution also has a significant portion above both other locations and a large tail. There are numerous approaches to handling this increased uncertainty, such as real options or minmax regret (e.g., risk avoidance versus cost avoidance).

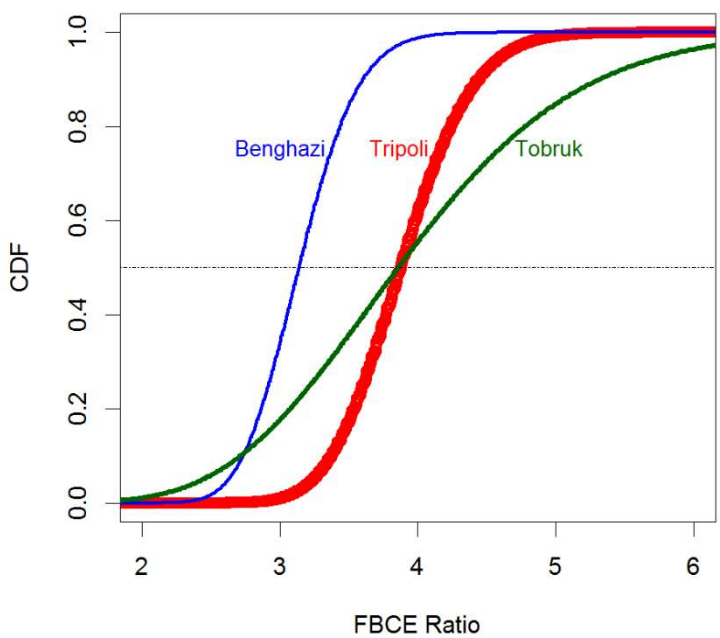

Figure 2.8: FBCE Ratio CDF for Rommel's Forces from 3 Port Locations

While relevance is difficult to quantify, this is level of information is certainly more than other methods could provide. Accordingly, this method creates a framework better suited to meet the changing and complex needs of an acquisition decision maker, increasing potential value [91].

2.8 Discussion

Unlike previous FBCE attempts, the proposed framework arms decision makers with a rapidly deployable, flexible method unrestricted by the data and assumptions of past military operations. Additionally, this framework meaningfully represents the uncertainty inherent in forecasting, which creates the opportunity to incorporate several dimensions of energy such factors as cost, risk, and resilience into decision making [83]. Such an approach may quickly become critically important as several force changing technologies loom on the horizon and threaten organization-wide reshaping, such as unmanned systems. The new F-35 may be the last manned strike fighter aircraft the Navy buys [92]. Paired with the dramatic increase in unmanned systems seen in practice and demanded in DoD force roadmaps, future logistic demands and lines may be radically different than those seen in even the most recent operations (e.g., unmanned aerial systems increased from 5% in 2005 to 41% of total sorties in 2012) [93]. Acquisition decisions will need to account for these changes as well as potentially significant differences between the future systems themselves.

Additionally, this framework could also be expanded to compare competing systems' performance across a common battery of randomly generated scenarios appropriately impacted by system-dependent demand. By considering a breadth of scenarios, the consequences of future energy demand can be better understood relative to other system costs and between competing systems. As a definable factor, sensitivity to uncertainty can also be evaluated. Reducing uncertainty can lead to scenarios with more specific FBCE estimates but that are less likely to occur in the future.

There are several important factors during an acquisition decision that are not currently incorporated into this framework. FBCE, or any such similar burdened logistic metric, are a part of the measure of a system's efficiency and sustainability. Efficiency and sustainability are important but do not entirely encapsulate a system's capabilities or operational value to the military [94]. Ultimately, the DoD exists to successfully carry out the objectives deemed important by the U.S. government. While prioritizing the mission, military commanders also highly value the lives entrusted to their care. Within this mindset, historic acquisition decisions have perceived increased logistic demand as a necessary consequence of or secondary consideration to increased combat capability. To truly understand the value of FBCE, it may be necessary to attempt to quantify it within the rest of a system's capability space and account for that which is interconnected with the opponent's capability and energy space [95]. This would allow for a detailed discussion of the value of reducing a system's potential logistic cost and risk that improves mission capability and saves lives within the greater system tradeoff analysis.

2.9 Conclusions, Policy Implications, and Future Work

Logistic costs have played a significant role in various military operations throughout history. Today, the operational DoD heavily relies on petroleum fuels. This represents a risk to the organization both because of that market's uncontrollable price volatility and a lack of understanding of the true cost of that dependency. Without a better understanding, the capabilities of future operations may be limited by logistic burden incurred by present-day acquisition decisions.

Attempts to demonstrate this cost and risk to the acquisition decision maker through FBCE have been mixed. While the regulatory requirement of such a metric demonstrates the perception of importance, current implementation tends to compare deterministically the cost of competing systems with relatively similar demand in a single scenario with an assumed level of usually low risk. This mindset had led to a simple metric relatively easy to implement within a large organization but one with little actual value. Stepping back and rethinking FBCE is necessary to capture these costs across a breadth of scenarios with widely varying risk and demand. This chapter outlined a framework by which a range of risk and fuel demand and their inherent uncertainty can be incorporated into a new energy metric. Through this, decision makers can focus on a couple of important factors impacting energy demand and mitigate long term costs and risk for the organization.

As this is an initial work rethinking the foundation of this energy metric, there is room for significant improvement. Adding value by increasing model complexity is not particularly difficult. The challenge is adding that which maximizes the marginal value per unit of additional complexity or determining some heuristics that also add or maintain value while simplifying application. Of course, focused and detailed analysis by stakeholders and the research community is necessary to determine where the tradeoffs exist for this area of research and is therefore warranted. In other words, the success of this or any similar energy metric is highly dependent on sustained support from senior military officials and above not only during implementation but through its entire use [96], [97].

Incorporating distributions into FBCE will likely complicate the defense of an acquisition decision, especially in a political context. As argued throughout, FBCE point estimates generated from assumed linear relationships poorly represent the reality of logistic burden and the uncertainty inherent in military operations. However, it is trivial to decide which of the competing systems' FBCE generated from such methods is preferred. Including uncertainty necessitates a wider discussion to understand the significance of such features as distribution spread and tails. Preferences may still be clear if stochastic dominance exists. Otherwise, a discussion of the cost and risk of various probabilistic outcomes may be necessary.

Additionally, given the fundamental connections between the design and implementation of FBCE and many other organization designed metrics, work on this has much to gain and give to many industries especially ones that deal with high uncertainty, high risk forecasting. Across industries, organizations rely on metrics to make decisions about risk. For every metric, organizations must face the same fundamental tradeoffs between such factors as accuracy, reliability, and ease of use. In fact, the entire process from metric determination and motivation through definition to implementation and integration is fraught with competing goals and pitfalls. Properly navigating these hurdles can result in valuable decision aiding metrics that can save time and money. Poorly designed metrics waste the time and money invested during development and implementation and quickly cloud already complicated decisions, creating competitive disadvantages for organizations as long as they remain in use. Lastly, while planning for contingencies is important to the military, the need also exists for many other industries [98].

Future work will implement the framework discussed across a range of scenarios and analyze the value such a metric could represent to an acquisition decision maker. This will include comparing historic and hypothetical systems' FBCE ratios across individual and ranges of scenarios.

2.10 References

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Chapter 3: Imperial Japan, Guadalcanal, and Fuel: The Military Cost of Energy Decisions

Abstract

This chapter examines the Imperial Japanese Navy's operational decisions surrounding Guadalcanal in World War II to explore the important and inseparable connections among military capabilities and energy costs. Because of this exploration, this analysis holds significance for future military planning as it highlights the operational impacts of balancing short-term and long-term logistic considerations under an inflexible doctrine. Lastly, because of all those connections, this work demonstrates the challenges of creating an energy metric that is simple enough to be incorporated into decision making processes, flexible enough to adapt to the fluid demands and constraints of operations, and complex enough to stress all the dimensions of energy. Yet if not confronted, there is a real risk that logistic and energy challenges and vulnerability will severely impede the capabilities of future U.S. forces and operations.

Logistic considerations belong not only in the highest echelons of military planning during the process of preparation for war and for specific wartime operations, but may well become the controlling element with relation to timing and successful operation [1].

Vice Admiral Oscar C. Badger, USN

... in its relationship to strategy, logistics assumes the character of a dynamic force, without which the strategic conception is simply a paper plan [1].

Commander C. Theo Vogelsang, USN

Underway replenishment was the U.S. Navy's secret weapon of World War II [1].

Fleet Admiral Chester Nimitz, USN

3.1 Motivation

The United States DoD consumes a tremendous amount of petroleum products on operations powering its portfolio of air, sea, and ground vehicles, as well as providing energy services to stationary and mobile groups of personnel. This dependence on petroleum-based fuels and sensitivity to market price uncertainty create a significant risk to the organization, which at the very least can lead to short-term disruptions in military operations [2].

The commodity cost of energy is arguably the least important component of the total cost of energy for many decision makers in the DoD. Energy has several first-order impacts on the operational capabilities of any system. Tactical systems that demand more energy create larger or more frequent resupply requirements that increase the probability and consequence of interdiction and energy disruption.

The heavy costs of logistics and the risk of shortfall are not simply creations of modern warfare. Technological innovations and changes to military strategy in the 20^{th} century only increased the consequence of inadequate logistics. During World War I, the historic main components of logistics, fodder and, to a less extent, food, were dwarfed by the ammunition requirements of magazine rifles and quick-firing artillery. Unlike the requirements they replaced, these could not be foraged and had to be manufactured and shipped to frontline forces. Though appreciable, transportation technological development was woefully inadequate for the scale of this task. Railways had sufficient capacity but where too vulnerable to artillery to approach frontlines and too inflexible to follow advances. Vehicles of the time were unavailable in sufficient quantities, and those available created their own logistic demands either with fuel if running or spare parts if not. Accordingly, the last part of the supply chains for this 20th century war with armies in the millions was largely comprised of horses and carts [3]. The logistic issues that plagued this war were a significant contributor to the siege-like trench warfare that characterized World War I.

World War II saw a continued growth of logistic needs with petroleum products taking center stage. The growth in the quantity and capabilities of ships, aircraft, and ground vehicles created opportunities for unprecedented strategies in previously inaccessible environments, while simultaneously limiting any unit's self-sustainability. There is no shortage of examples of commanders considering logistics in their operational decisions only in hindsight after supply shortfalls impacted capabilities (e.g., Rommel in Africa and Army Group North as they approached Leningrad) [3]. However, it is critical to note that operational failures associated with logistic shortfalls did not always occur because they were not considered or considered only second to operational objectives. This chapter examines the Imperial Japanese Navy's operational decisions surrounding Guadalcanal in World War II to explore the important and inseparable connections between military capabilities and energy costs. Because of this exploration, this analysis holds significance for future military planning as it highlights the operational impacts of balancing short-term and long-term logistic considerations under an inflexible doctrine. Lastly, because of all those connections, this work demonstrates the challenges of creating an energy metric that is simple enough to be incorporated into decision making processes, flexible enough to adapt to the fluid demands and constraints of operations, and complex enough to stress all the dimensions of energy. Yet if not confronted, there is a real risk that logistic and energy challenges and vulnerability will severely impede the capabilities for future U.S. forces.

The first three sections of this chapter provide background necessary to appreciate the context of the analysis. There is a section that briefly describes Guadalcanal's significance within the greater conflict, a section that reviews other previously documented factors in Japanese Naval decisions, and a third that reviews evidence of fuel's significance in decisions before the war and battles surrounding Guadalcanal. The following section examines two resupply options available to the Japanese Navy and compares their capability, energy demand, and logistic implications. The chapter concludes with recommendations for both the Japanese Navy of World War II and the U.S. military of today.

3.2 The Importance of the Guadalcanal Campaign

Though uncertain at the time, both Guadalcanal's outcome and significance are well known today. Earlier battles at Midway and Coral Sea are regarded as turning points in the Pacific theater and major American victories that significantly halted the rate of Japanese expansion [4]. Still, even after Midway, Japanese advances threatened communication and logistic lines between the United States, Australia, and New Zealand and put American bases in the area at risk. Accordingly by mid-1942, the US military decided it was time for offensive efforts in the Pacific. Initiated on the night of 6 August 1942 and ending on 9 February 1943, Guadalcanal, shown in Figure 3.1, was the first major campaign that sought to remove an island and an important airfield from the control of Japan's military, beginning a long road that eventually pushed Japanese forces back to their home islands [4]. With a focus on their navy, this paper argues that Imperial Japan's failures during this campaign are partly attributable to their failure to balance short- and long-term fuel resources and recognize when these were at odds or misaligned with their overarching doctrine. More simply, it highlights the importance of incorporating energy into military decision process while, at the same time, underscoring the difficulty of doing so.

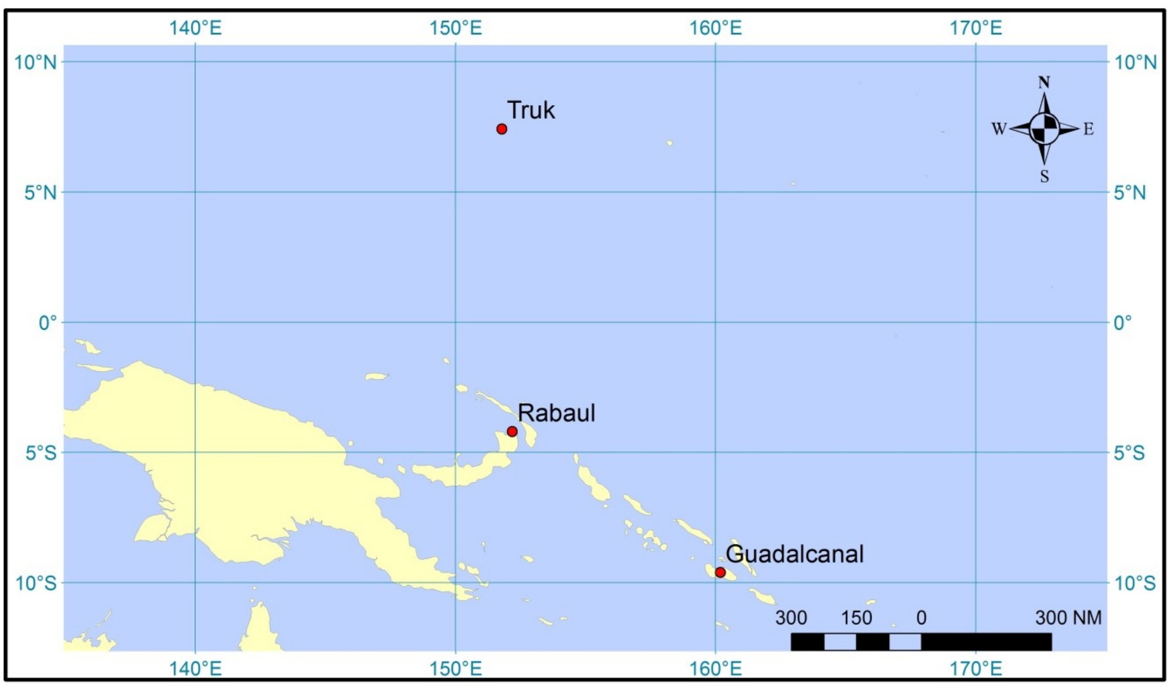

Figure 3.1: Guadalcanal and Possible Japanese Resupply Ports

3.3 Decision Making Factors of the Imperial Japanese Navy

Guadalcanal was a long and complex campaign for both sides, and this work does not attempt to address a subject that has filled volumes [4]–[7]. Instead, we focus on analyzing the connection between soldier resupply capability and fuel in this operation. Specifically, how the general desire to conserve fuel in the short-term perceived through a poor metric helped lead to resupply decisions that failed to both conserve fuel and achieve victory in the long-term. In Guadalcanal, one obvious consequence of this mentality was the lack of capital ships committed, which were used much more frequently at the same time in the Solomon Islands campaign [8]. If committed, they could have helped establish sea dominance in the area and provided the heavy pre-assault fires necessary to at least temporarily incapacitate Henderson Field [4]. This was especially true early on given the lack of comparable ships in the US fleet as the United States ramped up its industrial complex and focused on the European theater.

One conventional rationalization is that the Japanese Navy felt battleships were ineffective against airpower and too valuable to risk without air dominance [9]. While this may have been a part of it, this reasoning does not fully explain the decision process as they did risk their battleships later in the campaign. On the night of 13-14 October 1942, the Japanese battleships *Haruna* and *Kongo* bombarded Henderson Field with large-caliber incendiary shells. The bombardment heavily damaged both runways and destroyed most of the available aviation fuel and 48 of the 90 American aircraft [4]. Despite the hard work to restore one of the runways and the relocation of aircraft and fuel from Espiritu Santo, the bombardment created a gap in American airpower large enough for the Japanese to land a convoy of transport vessels. While some of these ships were eventually lost, it was successful enough for the Japanese to attempt again in November. This attempt proved much less successful for the Japanese, both in terms of incapacitating Henderson Field and landing troops and resulted in the loss of the battleship *Hiei* ultimately by American aircraft [4], [5], [10]. However, the *Hiei's* bombardment of Henderson

Field was avoided and its ability to depart hindered because of the sacrifices of the naval forces under Admiral Callaghan and Lee [4], [5]. As such, both examples contradict this rationalization and serve as evidence of inconsistencies within Japanese decision making.

A second, well documented, explanation holds that the Imperial Navy did not perceive the strategic significance of Guadalcanal and so their "Decisive Battle" doctrine did not support the allocation of capital vessels to the campaign. It was a doctrine created from the lessons of the Russo-Japanese War and was the cornerstone of strategy during the interwar period. While certain technological developments caused some Japanese decision makers to question it, the doctrine definitely played a role during World War II [9], [11], [12]. However, there are several examples that it was not religiously abided by even before Guadalcanal. The Battles of Coral Sea and Midway are two well-known examples of this doctrine being flouted.

Given the lack of these explanations to justify completely the absence of more capital ships, this work explores the involvement of a potential third factor, fuel considerations, and that factor's connection to military capability. Specifically, how the general desire to conserve fuel in the short-term perceived through a poor metric helped lead to resupply decisions that sought to both conserve fuel and achieve victory but failed to do either in the long-term.

3.4 Fuel as an Important Decision Factor in the Pacific Theater

Well before the beginning of the war, Japan was acutely aware of its indigenous resource limitations and tried to stockpile reserves. Since the 1890's, they had attempted to develop a domestic oil industry with American technology and assistance [13]. Their Seven-Year Plan in 1937 called for the completion of over 80 synthetic oil plants. By 1941, they had 21 operational refineries on the home islands.

The freezing of their U.S. assets by President Roosevelt in 1941 deprived them of about 80% of their oil imports and put them on a clock to take some action lest they burn through their reserves as imports at the time fell grossly below demand [14]–[16]. Ultimately, Japan went to war by prioritizing the capture of the Netherlands East Indies (NEI) oil fields and refineries on Borneo, Java, and Sumatra [13], [17], [18]. While necessary to maintain petroleum supplies, the production of the fields and refineries were appreciably degraded by the previous operator's preplanned sabotage and further exacerbated by American submarine attacks [17]. While initially US submarine operations were unfocused on tankers and few in number, the consequences of the American blockade grew as tactics were adjusted and support was added from additional, newer submarines, carrier-based aircraft, land-based aircraft, and mines mostly from B-29s.[11] Impacts from the American blockade were felt quickly because of Japan's improperly prioritized tanker fleet development. Japan entered the war with a 111-ship, 575,000-ton tanker fleet that peaked at 168-ship, 834,000-ton fleet by November 1943 and fell precipitously about one year later. Monthly oil imports to the home islands peaked at 1.75 million barrels in August 1943 but a little more than a year later, in October 1944, were down to 300,000 barrels [13], [17], [19].

As the largest consumer of oil in Japan, the Japanese Navy suffered the greatest impacts from fuel supply issues. As noted by others, the Imperial Navy began focusing on their large fuel consumption as early as May 1942 around the Battle of Midway well before the collapse of Japan's tanker fleet [13], [20]. The week-long Battle of Midway alone had consumed more fuel than the Japanese Navy had ever used before in an entire year of peacetime operations [12].

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[11] Hours after Pearl Harbor, President Roosevelt approved a message from Chief of Naval Operations (CNO) to Pacific commanders, authorizing them to "Execute Unrestricted Air and Submarine Warfare Against Japan" [16], [17].

Fuel also played a large role in nearly every aspect of the Battle of the Philippine Sea in June 1944. Prior to the battle, the Japanese forces had to be kept to the waters off Borneo to ensure availability of fuel, which increased their exposure to submarines. Accordingly, the fleet was put into port, which prevented their carrier aircraft from taking off [13], [20]. These pilots were poorly trained as training hours were cut in 1943 to save fuel [13], [19], [21]–[23]. When the order was given to engage the approaching US forces, not enough refined fuel was available so the supply vessles loaded up on volatile crude.[12]

As it did before, oil impacted every level during the battle. Tactically, "The Great Marianas Turkey Shoot" on June 19th and 20th resulted in the loss of 395 of the 430 Japanese aircraft involved and the explosion of the volatile fuel played a role in the sinking of both carriers. Operationally, this engagement marked the end of Japanese carrier power and the loss of the southern Marianas, which had both enormous logistic and strategic value to the Americans. Strategically, the loss of this battle served as a catalyst to the fall of the Tojo government [19], [20], [23]–[26].

Occurring chronologically between the Battle of Midway and Philippine Sea, the next section explores the role that fuel may have also played in operational decisions for Guadalcanal.

3.5 Fuel as an Important Decision Factor in Guadalcanal

The following analysis takes multiple slices through this dynamic and uncertain decision space to highlight its complexity, surmise the prevalence of fuel in the Japanese Navy's decisions surrounding Guadalcanal, reveal shortfalls in those decisions, and suggest possible

[12] Ships typically burn highly stable fuel removed of volatile hydrocarbons for safety reasons.

courses of action that might have improved their chances of success. Ultimately, we carry these lessons learned into future works.

Following the Battles at Tenaru and Eastern Solomons in August 1942, the Japanese lost control of the sea and dominance of the air around Guadalcanal. Whether perceived as impossible or unnecessary, these spheres of controls were never re-established. Instead, they adjusted their resupply tactics to avoid attacks from American aircraft at Henderson Field. This required the use of fast warships that could steam in, unload, and get out of the range of American aircraft in one night. This role was filled by destroyers (DD) and became known as the Tokyo Express [4]. There were several major downsides to this plan. First, the Tokyo Express had opportunity costs. It pulled destroyers from protecting other ships moving supplies, including petroleum products, around Japan's sphere of influence. Second, the Tokyo Express had limitations. Destroyers were not physically able to transport some of the larger or heavier equipment (e.g., tanks, anti-aircraft guns, howitzers) desperately needed by the Japanese ground forces to dislodge the dug-in Americans. Additionally, they could not generate effective pre-assault fires, leaving American capabilities unimpeded. Lastly, as a combination of the resupply distances, low capacity of these ships, and highly non-linear fuel consumption at higher speeds, these ships burned an immense amount of fuel for every soldier or ton of supplies delivered.

The twice-used alternative to the Tokyo Express was resupply with transport vessels. There were many advantages and disadvantages regarding their use. First, these ships did not have comparable escort capabilities so their use at Guadalcanal had much less impact on ship vulnerability elsewhere. Second, relative to destroyers, transport vessels had much higher capacity, could handle a much wider range of cargo, and consumed considerably less fuel.

However, these ships were also painfully slow and unable to accomplish resupply under the cover of darkness. As a result, they were far more exposed and vulnerable to American power, especially air power. Accordingly, when used, transport vessels were heavily escorted and usually veiled by capital ships. Overall, this option required the commitment of larger quantities of fuel and ships and greater coordination but delivered far more troops per run and had a demonstrated ability to impeded American capabilities.

Even as a conceptual example, there are many potential factors to consider from multiple perspectives that have uncertain connections to the overarching concepts of this chapter: energy, military capability, and logistics. We examine each resupply option separately, testing multiple metrics that put various aspects of these concepts into the same decision space. The options are then compared and conclusions drawn.

3.5.1 Resupply Option: Tokyo Express

This section analyzes the Tokyo Express, one of the two before mentioned resupply options. Historical data is used to gain insight on frequency, capability, and performance uncertainty of Tokyo Express runs. This information bounds later analysis in this chapter and Chapter 5. Then, vessel performance data is assessed and mission profiles created. We use the combination of historic information, performance data, and mission profiles to calculate several first-order energy metrics. These metrics and the following discussion illuminate the strengths and weakness of the Tokyo Express and the energy-related tradeoffs for the Japanese Navy during Guadalcanal.

To estimate how much fuel these runs consumed, Table 3.1 shows the runs that occurred between 4 September and 12 October, excluding those with incomplete information and those using assets other than destroyers to deliver supplies (e.g., seaplane carriers).

Table 3.1: Resupply Runs between 4 September and 12 October [4]
Note: DD = Destroyer, CL = light cruiser, CH = heavy cruiser

Date in 1942	Resupplying Vessels	Escorting Vessels	Soldiers Transported	Average Soldiers Per Ship	Other Supplies
Sep 4-5	6 DD	5 DD	1,000	166.7	
Sep 5-6	5 DD	None	370	74.0	Provisions
Sep 15-16	7 DD	None	1,000	142.9	
Oct 3-4	4 DD	None	320	80.0	16 ton provisions
Oct 3-4	3 DD	None	190	63.3	15 ton provisions
Oct 4-5	5 DD	None	750	150.0	24 ton provisions
Oct 5-6	6 DD	None	650	108.3	2 field guns & ammo
Oct 8-9	4 DD	None	560	140.0	18 mortars
Oct 9-10	7 DD	1 CL	1,170	167.1	
Oct 11-12	5 DD	3 CH, 3 DD	300	60.0	

As shown in the table, the Tokyo Express used destroyers both as resupply and escort vessels. Destroyers moving soldiers maintained their ability to defend themselves and otherwise use the weapon systems they had onboard. The designation of a destroyer as an “escort vessel” is merely based on whether soldiers were carried onboard with the intent to unload them at Guadalcanal. While some might question the benefit of allocating unloaded destroyers, especially when compared to the costs (e.g., additional energy consumption, opportunity costs, increased probability of detection, mechanical issue, or enemy interdiction, and marginal improvement to protection), the Japanese sometimes exercised this option. I make no attempt to differentiate the protective capabilities or vulnerability of a resupplying destroyer from one only escorting as it has no impact on the perceived importance of energy for the metrics calculated later. However, the analysis does maintain some differences between resupplying and escorting destroyers that are explained later.

Analysis was conducted two ways: first, ignoring other supplies and only focusing on the number of soldiers transport, and second, using a series of assumptions that converted them to “soldier equivalents” via weight. While it resulted in marginal changes to some of the metrics in later tables (e.g., fuel per soldier), the second approach did not change trends or the existence of inflection points. Given the intent of this work to highlight the importance of fuel and the aim to generate suggestive, rather than definitive results, the other supplies are ignored and the need for several assumptions removed.[13]

To gain insight into the uncertainties of the Tokyo Express, the best-fitting distributions for the number of and average soldiers per resupply destroyer are calculated. The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) are two methods to assess the relative quality of statistical models for a given set of data [27]. While they do so slightly differently, both criteria attempt to balance between goodness of fit and the number of distribution parameters. Based on these methods, the integer uniform distribution for the number of resupply destroyers and uniform distribution for the average number of soldiers per resupply destroyers are chosen and shown in Figure 3.2 and Figure 3.3.

[13] The results of the analysis using the second approach are shown in Appendix C.

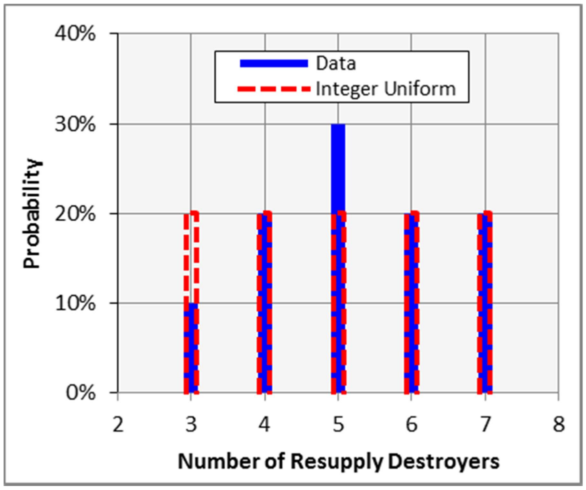

Figure 3.2: Fit Comparison for Resupply Size

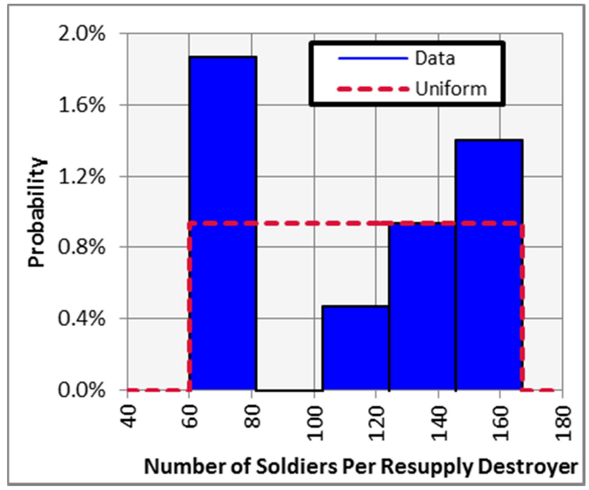

Figure 3.3: Fit Comparison for Soldiers Per DD

Based on these distributions, this first-order analysis assumes a convoy of three to seven *Hatsuharu*-class destroyers were used with escorts ranging from none to three heavy cruisers (CH) and three destroyers. Using the data median, it is assumed each of the supplying destroyers carries 114 soldiers with options to supply from Rabaul or Truk Island, shown in Figure 3.1. The mission profile is calculated by determining the total great-circle distance, which is then increased by 25% to account for the need to circumnavigate islands and avoid interdiction attempts from systems such as submarines. Next, assuming twelve hours of effective night cover, two hours to offload, and an effective American aircraft range of 150 NM, requires the supplying destroyers to travel at 30 knots for the five hours immediately preceding and following unloading. The critical fuel-related performance characteristics for the destroyers are shown in Table 3.2.

Table 3.2: Fuel Characteristics for Hatsuharu-class Destroyers [28], [29]

Speed (kts)	Radius (NM)	Endurance (hrs)	Capacity (tons)	Fuel Consumption (ton/hr)	Increase from Cruise
15	6,000	400	492	1.23	1.0
18	4,000	222	443	1.99	1.6
34	1,020	30	492	16.4	13.3

Based on that performance, an exponential regression is assumed and shown Figure 3.4 and Equation *3.1*.

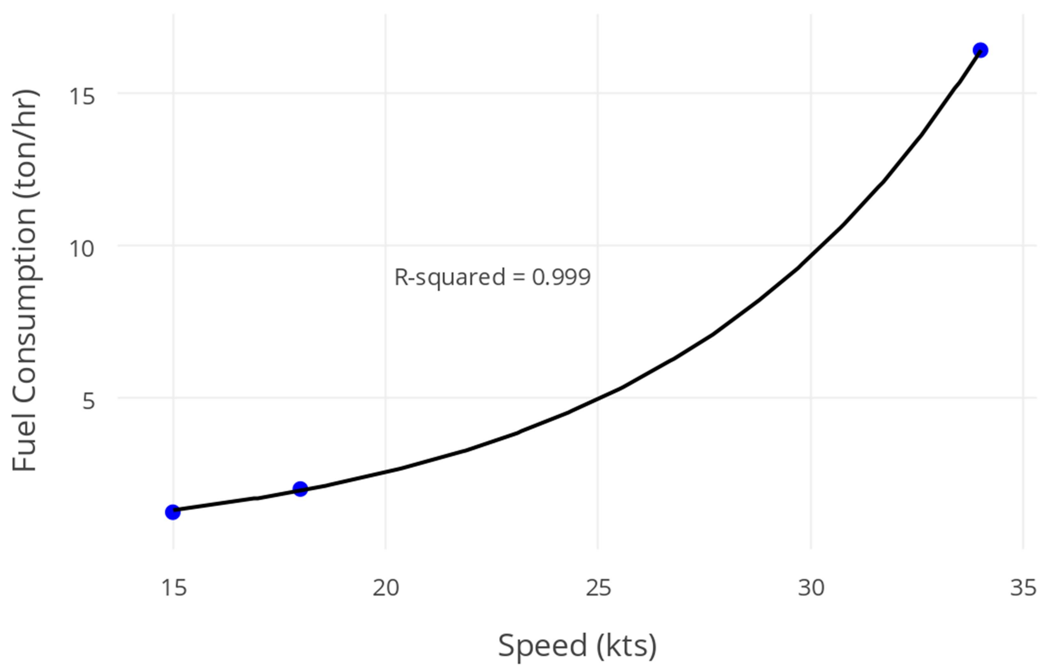

Figure 3.4: Fuel Consumption vs Speed for Hatsuharu-class Destroyers

$$Fuel\ Consumption = 0.169 * e^{0.135*Speed} \quad \textbf{3.1}$$

Given the limited performance data on the light and heavy cruisers, this work is unable to generate specific fuel consumption models, but because of their size and mission, their fuel consumption is assumed to scale similarly to Japanese battleships. Data from the Yamato is shown in Table 3.3 and the regression in Figure 3.5 and Equation 3.2.

Table 3.3: Fuel Characteristics for Yamato-class Battleships [30]

	Speed (kts)				
	16.5	23.2	25.6	26.6	27.5
Fuel Capacity (tons)			6,200		
Ship Horsepower (shp)	18,595	61,430	90,080	120,655	153,553
Fuel Consumption Per HP (kg/shp/hr)	0.466	0.442	0.419	0.395	0.371
Range (NM)	7,200	5,295	4,211	3,463	2,989
Endurance (hr)	437	228	164	130	109
Fuel Consumption (ton/hr)	8.67	27.2	37.7	47.6	57.0

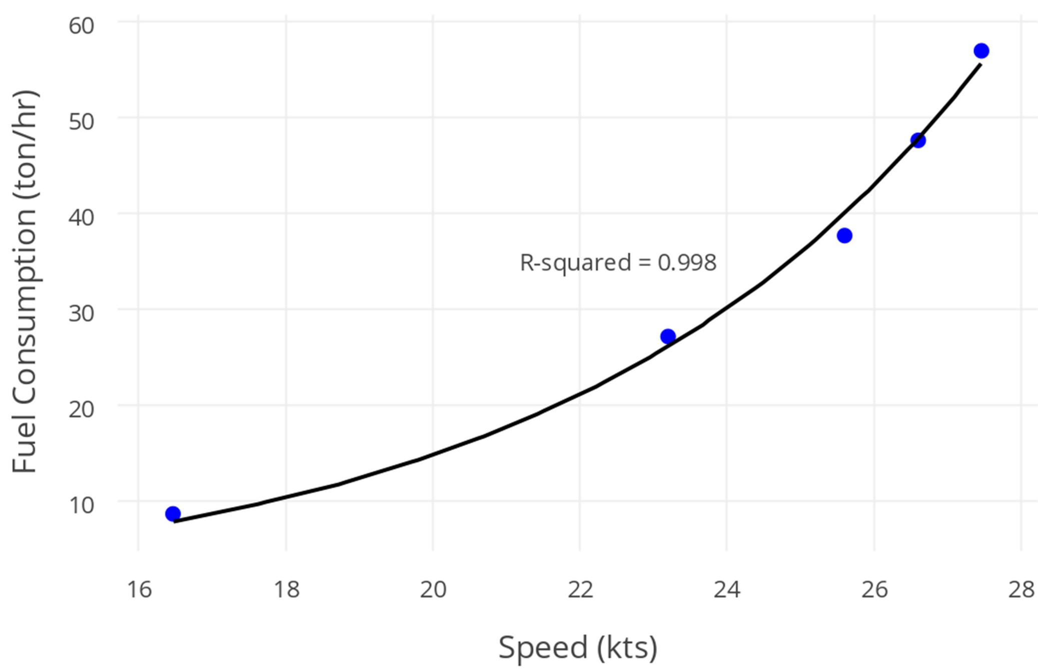

Figure 3.5: Fuel Consumption vs Speed for Yamato-class Battleships

$$Fuel\ Consumption = 0.540 * e^{0.168*Speed} \qquad (3.2)$$

Using this data, the fuel consumption rates at cruise for the light and heavy cruisers, 3.0 and 5.0 tons per hour, are estimated to increase approximately 2.0 times at 20 knots, 4.5 at 25 knots, and 8.9 times at maximum speed [31]–[35]. Finally, it is assumed that during unloading, the resupply destroyers have negligible fuel requirements, while the escorts are at fuel consumption rates commensurate with 20 knots in case of an attack. The resulting mission profile for one scenario with seven resupply destroyers escorted by three heavy cruisers and three destroyers from Rabaul is shown in Table 3.4.

Table 3.4: Mission Profile for 7-ship Escorted by 3CH and 3 DD Tokyo Express from Rabaul

Event	Speed (kts)	Round-trip Distance (NM)	Time in Event (hrs)	Fleet Fuel Consumed (tons/hr)	Ships Involved	Total Fuel Consumed (tons)
Cruise	16	1,200	75	29.6	13	2,220 (48%)
Run-in/out	30	300	10	230.0	13	2,300 (50%)
Unloading: DD	NA	NA	2	0.0	7	0 (0%)
Unloading: Escorts	20	NA	2	36.9	6	74 (2%)
					Total	4,590

As illustrated in the historic data, the Tokyo Express did not always depart from Rabaul nor consist of seven destroyers with the escorts assumed in the mission profile above. Table 3.5 shows the analysis expanded to 3-ship convoys and a destination of Truk Island (2,900 NM roundtrip), another possible departure point. Additionally, analyzing mission profiles serves to only highlight the troops delivered and fuel consumed per trip, which only illustrates one, short-term focused way to perceive the energy demands and capability of this resupply option. Accordingly, the table also displays the fuel consumed for a representative buildup, trips required for a representative buildup, and fuel per soldier delivered. Relative to per trip costs, the representative buildup and fuel per soldier serve to highlight long-term energy costs and efficiency, respectively. Additionally, the representative build-up metric might be easier to integrate into current planning metrics for a military decision maker. Ten-thousand soldiers was chosen as that number and more were transported to Guadalcanal several times throughout the campaign [4]. Lastly, to maintain awareness of resource limitations, each Tokyo Express variation's estimated fuel consumption is calculated as percent of monthly available. The percent of monthly available is based on annual production estimates in 1942 from the captured oil fields in NEI divided evenly into months, where the Imperial Japanese Fiscal Year (FY) ran from April to March and Guadalcanal occurred from August 1942 to February 1943 [13].

Table 3.5: Fuel Analysis of Tokyo Express

		Resupply Point							
		Rabaul (1,500 NM)					Truk Island (2,900 NM)		
Convoy	Resupply Vessels	7	3	7	7	7	3	3	3
Convoy	Escort Vessels	None	None	1 DD	1 CH	3 CH & 3 DD	3 CH & 3 DD	None	3 CH & 3 DD
Per Trip	Fuel (ton)	1,440	617	1,650	2,280	4,590	3,770	1,000	5,850
Per Trip	% Cruise	53%	53%	53%	50%	48%	47%	71%	66%
Per Trip	% Run in/out	47%	47%	47%	49%	50%	51%	29%	33%
Per Trip	% Unloading	0%	0%	0%	1%	2%	2%	0%	1%
Per Trip	Soldiers	798	342	798	798	798	342	342	342
Per Trip	% of Monthly Available	1.6%	0.7%	1.8%	2.6%	5.1%	4.2%	1.1%	6.6%
Per 10,000 Soldiers	Fuel (ton)	18,000	18,000	20,700	28,600	57,600	110,200	29,200	171,000
Per 10,000 Soldiers	Trips	12.5	29.2	12.5	12.5	12.5	29.2	29.2	29.2
Per 10,000 Soldiers	% of Monthly Available	20%	20%	23%	32%	64%	123%	33%	192%
	Fuel Per Soldier	1.8	1.8	2.1	2.9	5.8	11.0	2.9	17.1

As the table shows, shorter resupply distance and unescorted convoys reduce short-term (e.g., fuel per trip) and long-term energy demand (e.g., fuel per 10,000 soldiers) and improve energy efficiency (e.g., fuel per soldier). If decisions focus on reducing short-term demand and escorts are deemed unnecessary or unavailable, a preference may develop for smaller convoys with shorter resupply distances though this has no impact on long-term demand to move a certain number of soldiers or efficiency. If escorts are required, larger convoys increase short-term demand for fuel but decrease long-term demand and improve efficiency.

At this point, the analysis has several limitations. The preference for smaller convoys fails to account for many potentially significant relationships, which may meaningfully impact all these measures of energy (e.g., smaller, more frequent convoys may be easier to interdict by enemy forces and losses from such interdictions are historically independent of convoy size so smaller convoys suffer higher losses as a percent) [36]. Also the representative build-up metric allows marginal utilization, meaning it does not account for the energy step-function costs of the resupply options and, as such, the long-term total energy demand metric demonstrates the same trends as the efficiency one. Later this is remedied but for now serves as bridge between tactical and operational energy considerations. In addition, this analysis does not include: one, the fuel needed to deliver fuel to Rabaul or Truk Island, two, contain the costs and benefits of launching air raids, which frequently occurred during these resupply missions or, three, allow for appreciation of the underlying uncertainty. For now, these factors are ignored to show a starting point for how zeroth-order energy metrics create preferences that may significantly change as relationships and factors are added. Some of these issues are remedied below and some in Chapter 5.

3.5.2 Resupply Option: Transport Vessels

As previously mentioned, the Imperial Japanese Navy bombarded Henderson Field on 13-14 October 1942. This coincided with the landing of six transport vessels, which, though slower moving than destroyers, could move much larger quantities of soldiers and heavier equipment. On that evening, a task force of two battleships, escorted by nine destroyers and the light cruiser (CL) *Isuzu* approached the island from the north to begin a bombardment. For the remainder of this analysis, this group of vessels is referred to as the bombardment group. The attack from the bombardment group covered the approach of six fast transport vessels, which were escorted by eight destroyers. The transport vessels were able to deliver approximately 4,500 troops, one battery each of 10 cm and 15 cm howitzers, a battalion of antiaircraft guns, a tank company, and stocks of ammunition and provisions [4]. Because of data availability, the fuel consumption for the transport vessels is modeled after the highest found for the Liberty ship, which should conservatively estimate fuel consumption given the larger size of that ship [37]–[39].[14]

The previous mission profile and its assumptions are replicated with the following exceptions. Because the transport vessels are speed limited, the bombardment group is limited to 25 knots [30]–[32]. Additionally, the transport ships maintain 10.5 knots throughout their entire profile and their escort destroyers 15 knots. These are assumed to be the fastest maintainable speed by the transport vessels and the slowest economical speed for the destroyers. The resulting mission profile for the combined fleet from Rabaul is shown in Table 3.6.

Table 3.6: Mission Profile for Bombardment Fleet and Transport Vessels from Rabaul

	Event	Speed (kts)	Round-Trip Distance (NM)	Time in Event (hrs)	Fleet Fuel Consumed (ton/hr)	Total Fuel Consumed (ton)
Bombardment Group	Cruise	16	1,200	75.0	32	2,410 (40%)
	Run-in/out	25	300	12.0	130	1,560 (26%)
	Unloading	NA	NA	2.0	60	120 (2%)
					Subtotal	4,090 (68%)
Transport Fleet	DD escorts	15	1,500	100.0	10.2	1,020 (17%)
	Transports	10.5	1,500	142.9	6.6	950 (16%)
					Subtotal	1,970 (32%)
					Total	6,050

Based on historic record, this option is viewed as the cooperative effort of the following three components: the resupply transport vessels, their escort destroyers, and the bombardment group. Table 3.7 shows this mission profile expanded to partial and no escort scenarios and Truk

[14] Compared to the transport vessels used, the Liberty ship had a 6-11% higher deadweight tonnage and 4-15% higher gross registered tonnage [38], [49].

Island, fuel consumed and trips required for a representative buildup, and fuel per soldier. The partial scenario is this resupply option without the bombardment fleet, and the no escort scenario removes both the bombardment fleet and the escorting destroyers.

Table 3.7: Fuel Analysis of Transport Vessel Option

		Resupply Point				
		Rabaul (1,500 NM)			Truk Island (2,900 NM)	
	Fleet Mix	Transports	Transports & DD Escorts	Transports, DD Escorts & Bombardment Group	Transports	Transports, DD Escorts & Bombardment Group
Per Trip	Fuel (ton)	945	1,970	6,050	1,830	10,700
	Soldiers	4,500	4,500	4,500	4,500	4,500
	% of Monthly Available	1.1%	2.2%	6.8%	2.0%	12%
Per 10,000 Soldiers	Fuel (ton)	2,100	4,370	13,500	4,060	23,800
	Trips	2.2	2.2	2.2	2.2	2.2
	% of Monthly Available	2.4%	4.9%	15%	4.6%	27%
	Fuel Per Soldier	0.21	0.44	1.3	0.41	2.4

The analysis at this point does not attempt to include the cost of Japanese losses to resupply or escort vessels or the costs and benefits of the battleship bombardment, the regular Tokyo Express run that made landfall around the same time successfully unloading 1,110 soldiers and ammunition at Cape Esperance, or any air raids that occurred during this time interval. Again, at this point, the analysis ignores these for the same reasons given above. Given the limitations of data and analysis, the table demonstrates fairly intuitive trends, where the short-term and long-term energy demand are reduced and the efficiency improved by reducing resupply distance and the number of escorts.

3.5.3 Discussion

The real value of this latter analysis is in comparing the base case, the transports, DD escorts, and bombardment group case, with the costs of Tokyo Express option. Depending on priorities within, or perception of, the Guadalcanal campaign, the Tokyo Express option may seem like the better choice. All analyzed versions of the Tokyo Express required less fuel per mission than the transport base case, even when sent from Truk Island with full escort. It also didn't require the commitment of large quantities of fuel (e.g., opportunity costs) or any capital ships (e.g., risk of loss or opportunity costs). So in the beginning of the campaign, when the opportunity for their victory was the greatest, the Japanese's inability to perceive Guadalcanal as a decisive battle combined with their awareness of their limited fuel resources could have made the Tokyo Express a very attractive option.

Still even that trivializes the difficulty of defining the line between short-term and long-term energy planning for a military decision maker. Figure 3.6 shows the total fuel demand for a given number of soldiers from Rabaul, the same metric as shown in the above tables, across the resupply options, but now accounts for energy step costs. Variations of the Tokyo Express option are plotted as solid lines. The number of resupply destroyers and escorts are displayed as

$$X \text{ DD } (Y/Z)$$

where X is the number of resupply destroyers, Y is the number of escort destroyers, and Z is the number of escort heavy cruisers. Variations of the transport vessel option are shown as dotted lines.

The figure clearly illustrates grouping around escort options. The Tokyo Express permutations with the largest number of escorts have the highest demands with those of the 3 destroyer resupply significantly outpacing those of the 7 destroyer one. Below those are the lightly escorted Tokyo Express variations and below those the unescorted ones.

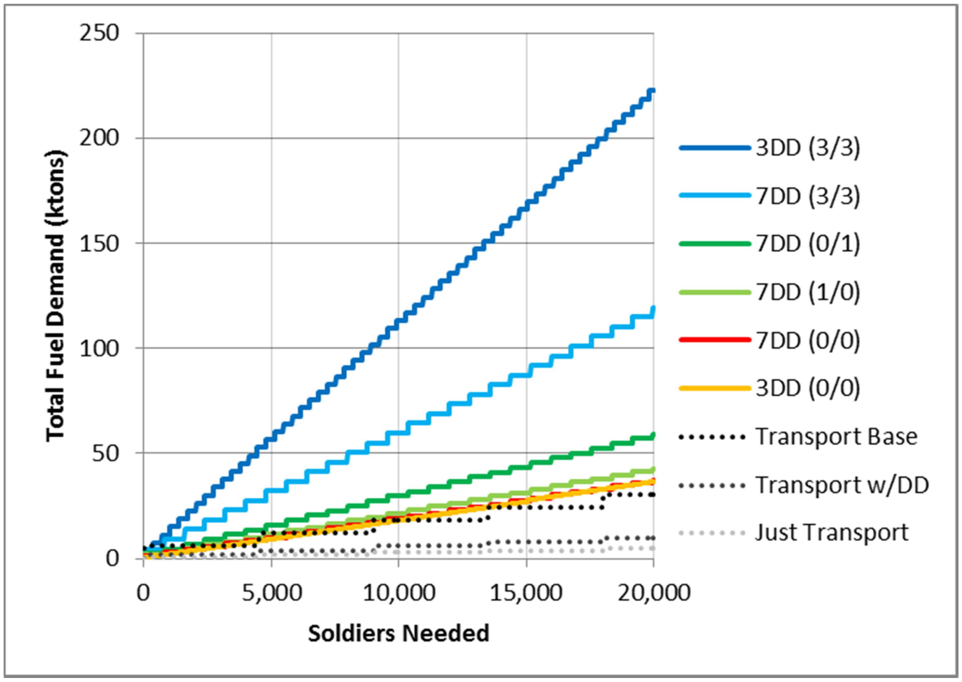

Figure 3.6: Total Fuel Demand for Resupply Options from Rabaul to 20,000 Soldiers

As implied by the previous discussion and a comparison between the per trip and representative build-up metrics, every Tokyo Express version analyzed has a crossover point with the transport base case. If the total soldiers needed is less than that quantity, it is the better choice even in the long-term. This is much easier to see in Figure 3.7, where Tokyo Express variations with similar fuel demand trends are removed to reduce congestion.

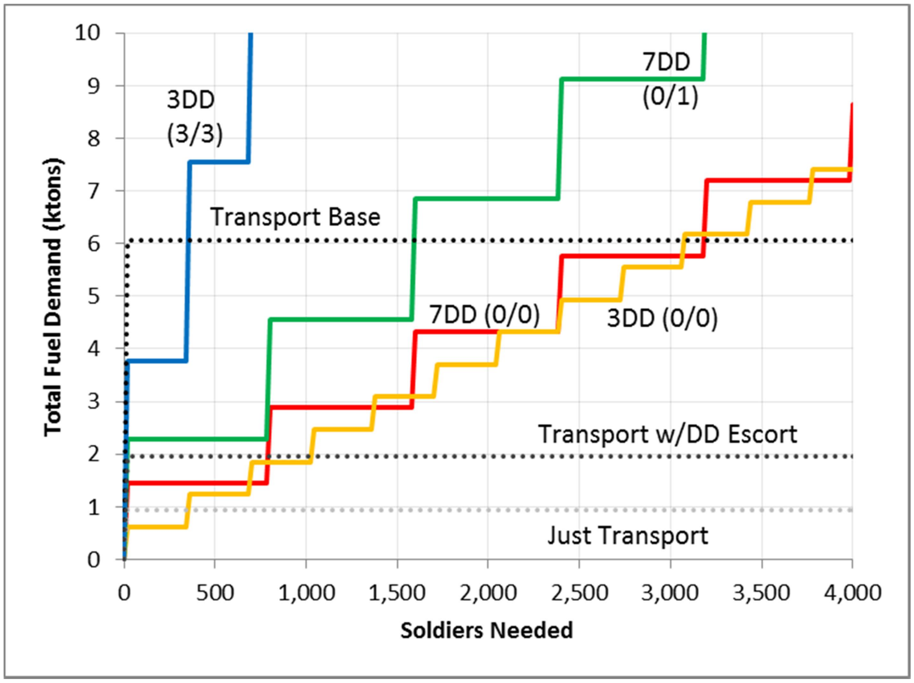

Figure 3.7: Total Fuel Demand for Resupply Options from Rabaul to 4,000

However, this is still incomplete. Even without uncertainty, some of the Tokyo Express options have multiple crossover points as shown in Figure 3.8. Accordingly, from a fuel standpoint, the preferred resupply option may not necessarily be the most efficient as soldier demands increase but instead depend more precariously on understanding the number of soldiers needed and the fuel step costs of resupply. For example, if the number of soldiers needed is known a prior to be exactly 10,000 then either unescorted version of the Tokyo Express can meet this operational demand with about the same amount of fuel without any of the downsides of the transport vessel option. If the needed build-up is uncertain, probabilities of preference are calculable if distributions on that uncertainty are determinable. This reveals an additional strength of the Tokyo Express. Since the number of needed soldiers is not entirely known *a priori*, the lower fuel per trip of Tokyo Express allows a finer resolution of build-up that may result in lower fuel waste in the long-term.

Figure 3.8: Expanded Total Fuel Demand for Resupply Options from Rabaul to 12,000

Additionally, while not directly addressed in this level of analysis, the ability to use and the cost of using these various resupply options are not independent of the option itself. Given the limitations of the escorting ships, there is only a small chance the sustained use of even heavily escorted Tokyo Express runs would impact the capabilities of the American forces unless the soldiers that they delivered were successful themselves. Occasionally, a few American aircraft were lost in attempts to impede the Tokyo Express. However, the capabilities of the American forces were largely unaffected by these small losses, which were mitigated in the short-term by relocating assets from within the area and eventual replacement. Therefore, by using the Tokyo Express, the Japanese Navy limited their ability to influence directly their resupply loss rates while reducing resupply escorts. On the other hand, while creating more risk and larger energy demands upfront and creating potentially large opportunity costs, the sustained commitment of a large bombardment force might have had lasting impacts on the capabilities of American forces. This could significantly lower the loss rates of using transport vessels and the number of necessary escorts in the long-term, dramatically impacting the energy costs of this option and improving its advantage over the Tokyo Express option. This consideration's impact on analysis is addressed in that previously mentioned paper.

Table 3.8 summarizes some of the strengths and weaknesses of the resupply options.

Table 3.8: Summary of Strengths and Weaknesses

Resupply	Strengths	Weaknesses
Tokyo Express	Less opportunity cost from otherwise occupied ships	Fewer soldiers per trip
	No risk to capital ships	-Certain operations may not be possible with intermediate build-ups
	Less fuel per trip (e.g., finer resolution that may result in less long-term energy waste)	-Wait times between build-ups may create large sustainment requirements
	-Across certain operational demands, able to deliver soldiers needed with less fuel waste	Significantly less efficient (fuel per soldier)
	Less ships involved	Small probability of impacting opponent's capabilities
	-Less coordination needed	-Fewer ways and smaller probability of creating battlespace with cheaper resupply options
	-Less chance for operational mistakes	-Small probability of establishing sea and/or air dominance
	-Less chance for opponent intercepting coordination	Inability to deliver certain weapon systems
	-Less chance for opponent noticing soldier and ship buildup	Higher frequency of resupply required may increase loss rates
Transport Vessel	More soldiers per trip	Higher opportunity costs
	-Operations may be able to commence immediately upon resupply	Risk to capital ships
	-Intermediate sustainment of forces may be less critical	More fuel per trip (e.g., courser resolution that may result in more long-term energy waste)
	Significantly more efficient	-More likely to generate appreciable fuel waste
	Larger probability of impacting opponent's capabilities	More ships involved
	-More ways and higher probability of creating battlespace with cheaper resupply options	-More coordination needed
	-Larger probability of establishing sea and/or air dominance	-Higher chance for operational mistakes
	Able to deliver a wide array of weapon systems to meet operational demands as campaign changes	-Higher chance for opponent intercepting coordination
	Lower frequency of resupply may allow tactics to decrease loss rates	-Higher chance for opponent noticing soldier and ship buildup

3.6 Conclusions

In summary, as the campaign developed, the Japanese Navy was unable to navigate between her "Decisive Battle" doctrine and a desire to obtain the most from her limited petroleum resources. At the start of Guadalcanal, these may have appeared to encourage the same strategy. In the beginning, Guadalcanal did not fit the classic perception of a "Decisive Battle" and, as such, did not deserve or require the allocation of capital ships [11], [12]. Possibly because of a number of other well-documented issues within the Japanese military (e.g., hubris, lack of credible intelligence and counterintelligence, and inability to adapt), the small number of troops that could be brought by destroyers may have seemed to be enough to dislodge the American forces, while keeping fuel expenditure low [40]–[47]. In hindsight, neither of these assessments turned out to be correct, and the combination of all these factors resulted in a strategy that failed to plan properly for the possibility of failure and both its financial and operational costs. In the long-term, their doctrine prevented the allocation of the very vessels that could have secured victory and saved limited resources when the American foothold and ability to resupply was most tenuous. Additionally, the use of destroyers proved unable to resupply enough soldiers and heavy equipment to be successful, while still consuming significant fuel, suffering appreciable losses, and worsening the exposure of an already insufficiently protected merchant marine fleet. It was a strategy with not enough committed to win or encourage withdrawal. In the end, the lack of Japanese capital ships and use of a destroyer supply-chain strategy proved more valuable to the American forces as it created a battle of attrition bleeding both sides of resources but impacting the Japanese more because of their chosen resupply option.

While even in hindsight it is unclear whether victory was achievable, this analysis suggests the Japanese Navy might have been better off from a fuel perspective by choosing either of the available options (e.g., not attempting to retake Guadalcanal or fully committing to the campaign and using capital ships to escort transport vessels for large-scale resupply early). The Japanese had a basic issue with logistic throughput. Given the use of destroyers, they could not deliver the right equipment. Given the use of the destroyers and the equipment that they could deliver, they could not deliver enough soldiers relative to their operational tempo and the American buildup. Given the use of destroyers and the equipment and soldiers that they could deliver, they could not deliver enough food. Of the roughly 30,000 soldiers sent to Guadalcanal, around three-quarters of the 20,000 that died did so for noncombat causes [48]. They needed to fully commit early and then have some way of assessing logistic means as a function of capability needs and energy resources.

It is a mistake to view this particular example as an interesting but abstract note in history. First, this serves as a valuable example of the tradeoffs between and the difficulty of balancing long- and short-term energy considerations with operational capabilities within strategic goals. Second, this demonstrates the need to inform decision makers with a metric that properly highlights all the areas energy extends into including short- and long-term cost, risk, and capability. Without which any future tradeoff analysis will likely mislead military decision makers and increase the probability of energy demands and logistic vulnerabilities negatively impacting military capabilities and chances of meeting strategic goals.

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Chapter 4: An Examination of Burdened Energy Decision Tools in the DoD Since 2001: A Problem Still Looking for a Solution

Abstract

This chapter analyzes the evolution of the conversation surrounding energy and FBCE within the DoD over the last 15-years. While details vary at the different levels of the organization, the trends within the DoD and her various services are similar. As a concept, FBCE is legally defined in 2008. Reports prior to that begin a discussion on the importance of energy and argue for its incorporation in various decision-making processes and tradespace analyses. However, though focus on application initially follows that growing understanding, progress grievously falters after initial attempts are unsuccessful. Unfortunately, these missteps coincided with several important events that may have doomed FBCE. Though it is speculation supported by publicly available information, the DoD's withdrawal from Iraq and Afghanistan and significant budget reductions seem to be primary contributors. The first removed the impetus for reform created by two simultaneous campaigns both with relatively long and vulnerable logistics. The second removed the resources to support the reform. Today, the DoD and DoN still do not have an energy metric that properly highlights the costs and consequences of energy-related choices to decision makers.

I don't know what the hell this 'logistics' is that Marshall is always talking about, but I want some of it [1].

Fleet Admiral E. J. King: To a staff officer. (1942)

Amateurs think about tactics, but professionals think about logistics [1].

General Robert H. Barrow, USMC (Commandant of the Marine Corps) noted in 1980

4.1 Motivation

The United States DoD consumes a tremendous amount of petroleum products on operations powering its portfolio of air, sea, and ground vehicles, as well as providing energy services to stationary and mobile groups of personnel. This dependence on petroleum-based fuels and sensitivity to market price uncertainty create a significant risk to the organization, which at the very least can lead to short-term operational disruptions [2].

The commodity cost of energy is arguably the least important component of the total cost of energy for many decision makers in the DoD. Energy has several first-order impacts on the operational capabilities of any system. Tactical systems that demand more energy create larger or more frequent resupply requirements that increase the probability and consequence of interdiction and energy disruption. Some historic examples showing capability consequences and other costs of using metrics that fail to incorporate energy in all its dimensions into decision processes or do so poorly were highlighted in Chapters 2 and 3.

Qualitatively, these risks are understood. Originally known as Fully Burdened Cost of Fuel, the DoD created a metric in 2007 now known as Fully Burdened Cost of Energy (FBCE) to better value these hidden costs during the acquisition process. FBCE attempts to quantify all the major costs assumed by the DoD when satisfying the future energy demands of competing systems (e.g., combat ground vehicles, support aircraft, or generators) in their potential operational environments. Its calculation is required at acquisition for certain programs, but its method of calculation is not standardized.

Originally, FBCE was embraced by all DoD Service Branches. Anecdotally, while its importance seems to be better understood and more accepted, support for FBCE has waned significantly since 2012. While regulation requirements are still satisfied, the limitations of its early versions were attributed to the concept, not application methods, and most developmental work ceased. For some stakeholders, the presence of FBCE in its current form may worsen the issue as it creates the perception that this is appropriately addressed when it is not [3]. Most recently, a concept without detailed guidance known as Energy Supportability Analysis (ESA) has replaced FBCE in some regulations (e.g., 2015 Joint Capabilities Integration and Development System Manual) though not all (e.g., July 2015 DoD Directive 4180.01 Energy Policy) [4]–[6].

This chapter focuses on the modern history of FBCE and the evolution of energy's perception within the DoD and DoN in general.

4.2 FBCE History

This chapter reviews the history of one attempt to better inform military acquisition decision makers by observing the development of the FBCE metric. The first section focuses on the history of guidance and directives from the DoD and Federal Government level, while the second and third sections focus at the Department of Navy and Marine Corps levels. Because of the number of offices that helped shaped the role of it and our interest in only using publicly available documentation, a complete history of FBCE is very lengthy and difficult to assemble.

While there may be some disagreement between the significance of some documents, every attempt was made to present a history in a single article that maintains accuracy without being unnecessarily exhaustive.

While details vary at the different levels of the organization, the trends within the DoD and her various services seem the same. As a concept, FBCE is legally defined in 2008. Reports prior begin a discussion on the importance of energy and argue for its incorporation in various decision-making processes and tradespace analyses. Aided by an era of conflicts with long logistic lines and heavy force sustainment costs, acceptance of energy's significance progressed quickly. However, though focus on application initially follows that growing understanding, progress on ways to incorporate energy into decision-making processes and tradespace analyses falters shortly after initially unsuccessful attempts. Today, the DoD and DoN still do not have an energy metric that is simple enough to be incorporated into decision making processes, flexible enough to adapt to the fluid demands and constraints of operations and planning, and complex enough to stress all the critical dimensions of energy.

4.2.1 Within the DoD

This section contains an overview of the history of FBCE on the DoD organizational level. As previously mentioned, this history shows a growing understanding of energy's importance. This initially translates to a budding interest in discovering a way to properly translate this to various decision makers. Presently, though appreciation remains, early application shortfalls seemed to have stunted further attempts.

The need for such a metric was first identified in a 1999 Defense Science Board (DSB) memorandum commissioned by the Office of the Secretary of Defense Acquisition, Technology and Logistics (OSD (AT&L)) [7]. Following that memorandum, several reports emerged stressing the critical importance of finding a way to incorporate a system's logistic footprint into the acquisition process and stem the alarming growth of operational energy demands. A 2001 DSB report stated that "the task force found that these benefits [of energy efficiency], and the burden to warfighting capability of not focusing on efficiency, were not factored into decision-making" [8]. While situation dependent, this same report also noted that the "standard price" used in many decision making processes may represent just a sliver of the true cost. For example, at the Air Force organizational level, this translated to a total embedded cost of $17.50 per gallon of in-flight delivered fuel versus $0.20 per gallon at the Defense Energy Support Center supply point; a difference that was causing the Air Force to spend 84% of their fuel delivery budget to deliver 6% of its fuel and would impact any life cycle analysis for any Service that might use in-flight refueling.

In September 2006, a report by the JASON defense advisory group remarked that

> "[f]uel use is characterized by large multipliers and co-factors...it takes fuel to deliver fuel….[It] imposes large logistical burdens, operational constraints and liabilities and vulnerabilities: otherwise capable offensive forces can be countered by attacking more-vulnerable logistical-supply chains" [9].

A month later, the John Warner National Defense Authorization Act (NDAA) of FY2007 legally bound the connection between energy, logistics and military capability. It stated "DoD's policy is to improve the fuel efficiency of weapons platforms…to enhance platform performance and to reduce fuel logistics systems" and recognized the "burden [that] high fuel consumption places on agility" and the "financial impact of volatile oil prices" [10].

In March 2007, Deputy Under Secretary of Defense for Logistics and Materiel Readiness announced changes to the acquisition process aimed at more directly accessing energy-related system attributes during procurement. The memorandum established Materiel Availability as a Key Performance Parameter (KPP) and Material Reliability and Ownership Cost as related Key System Attributes (KSAs) [11]. These changes had come from an earlier Joint Requirements Oversight Council (JROC) with planned inclusion into a revised version of the Chairman of the Joint Chiefs of Staff Manual 3170.01C. This manual informs operation of the Joint Capabilities Integration and Development System (JCIDS). When released, this manual stated fuel within these new factors would "be based on the fully burdened cost of fuel" [12].

In response to this increasing understanding, two DoD offices in the middle of 2007 attempted to establish a means of calculating a fully burdened cost metric. In April 2007, AT&L released a memorandum that established three pilot programs to test a new framework and stated that

> "[e]ffective immediately, it is DoD policy to include the fully burdened cost of delivered energy in trade-off analyses conducted for all tactical systems with end items that create a demand for energy and to improve the energy efficiency of those systems, consistent with mission requirements and cost effectiveness" [13].

Showing further understanding of energy's importance that hadn't had time yet for application, Crowley et. al. released a report the same month. That report identified three major areas of disconnect between the DoD's current energy consumption practices and the capability requirements of its energy strategy [14]. First, dependence on foreign fuel limited the DoD's strategic flexibility when "dealing with producer nations who oppose or hinder our goals for greater prosperity and liberty." Next, DoD operational goals have resulted in significant energy consumption with predicted upward trends. Lastly, the report recommended bridging the fiscal disconnect, in part, by

> "incorporate[ing] energy considerations (energy use and energy logistics support requirements) in the department's key corporate processes: strategic planning, analytic agenda, joint concept and joint capability development, acquisition, and planning, programming, budgeting, and execution (PPBE)" [14].

A few months later, Program Analysis and Evaluation (PA&E) released a memorandum that created a rudimentary methodology for a metric coined Fully Burdened Cost of Fuel (FBCF) [15]. Components of this methodology appeared in the first released versions of a spreadsheet tool by AT&L that became the starting point for some of the Services.[16]

Despite this progress, a DSB report released in February 2008 reached several important conclusions, including:

> "The Department [of Defense] has no consistent methodology to simulate the battlespace conditions created by high fuel re-supply requirements during campaign analyses, war gaming or staff training exercises. This makes fuel[-]supply consequences invisible to operations and force planners."

> "DoD has not yet fully implemented two key recommendations from a 2001 DSB Task Force on energy – establish a Key Performance Parameter (KPP) to constrain battlespace fuel demand; and establish the fully burdened cost of fuel (FBCF) to guide acquisition investments for deployed systems. This Task Force recommends the Department accelerate implementation of these, and that the Deputy Secretary exercise oversight" [17].

This report is interesting in that is shows the DSB seems to be aware of efforts by offices like PA&E as evident in the common language and terminology. Still, there is clearly a desire design for more progress.

In March 2008, the Deputy Director of AT&L testified before the House Committee on Armed Services Readiness Subcommittee demonstrating greater acceptance and understanding within the DoD trying to be translated to Congress. He highlighted the following two reasons for using FBCF: first, for decision makers to gain insight on the risks generated by the huge DoD fuel demand; second, to open up science, technology, and acquisition "if we properly valued the financial costs of delivering fuel to the operator" [18].

In July 2008, AT&L issued a memorandum that reinforced the implementation of FBCF into the KPPs and life-cycle management framework, reinforcing perceived importance within those processes [19]. Similar significance of the concept in general and FBCE in particular was echoed in the Duncan Hunter NDAA for FY2009, mandatory DoD instruction (DoDI) 5000.02, and the Weapon Systems Acquisition Reform Act (WSARA) [20]–[22].

Codified in Title 10 U.S.C. 2911 §332, the NDAA for FY2009 required analyses to consider fuel logistics requirements and vulnerability and required fuel efficiency to be included as a Key Performance Parameter (KPP) putting it on par with other KPPs, such as lethality and protection. Paragraph (c) also stated that:

> "The Secretary of Defense shall require that the life[-]cycle cost analysis for new capabilities include the fully burdened cost of fuel during analysis of alternatives and evaluation of alternatives and acquisition program design trades."

Additionally, the law created a legal definition for FBCF in paragraph (g):

> "…the commodity price for fuel plus the total cost of all personnel and assets required to move and, when necessary, protect the fuel from the point at which the fuel is received from the commercial supplier to the point of use" [21].

Furthermore, the NDAA for FY2009 required separate energy performance master plans for each department or agency, broadening the scope created by the NDAA for FY2007, and compelled specific metrics to measure the progress towards achieving energy performance goals.

In addition to defining FBCF and requiring its calculation, the NDAA for FY2009 also created the office of Operational Energy Plans and Programs (OEPP) and appointed a director [21]. This was codified in Title 10 §138c and resulted in DoD Directive (DoDD) 5134.15 [23], [24]. This position was responsible for establishing a Department-wide strategy for operational energy and ensuring the DoD proposed budget adequately implemented the established strategy. DoDD 5134.15 also formalized the definition of operational energy as:

> "The energy required for training, moving, and sustaining military forces and weapons platforms for military operations. The term includes energy used by power systems, generators, logistics assets, and weapons platforms employed by military forces during training and in the field. Operational energy does not include the energy consumed by facilities on permanent DoD installations, with the exception of installations or missions supporting military operations. Operational energy does not include the fuel consumed by non-tactical vehicles" [24].

A similar but short definition was located in the NDAA for FY2009 §331.[21]

A new version of DoDI 5000.02, released in December 2008, stated that "The fully burdened cost of delivered energy shall be used in trade-off analyses conducted for all DoD tactical systems with end items that create a demand for energy." Though recently created, this instruction also broadened FBCF to include all energy in 2008, and the concept was renamed Fully Burdened Cost of Energy (FBCE) though the intent remained unchanged [20].

Introduced in February 2009, the WSARA of 2009 never mentioned FBCE directly but discussed energy, logistics, and acquisition outcomes. It stated that unexpected costs, including energy costs, and logistic burden are some of the many possible undesirable acquisition outcomes. This act attempted to create additional impetus for more consideration of these undesirable outcomes and, given the time of its release, the newly required FBCE was probably one of the tools expected to help remedy this issue [22].

Released that same month, an updated version of the JCIDS Manual in 2009 added some important language to the previously created acquisition parameter. It stated that, as part of the Energy Efficiency KPP, fuel efficiency should be considered as a function of "future force plans" and fuel-related risk. Furthermore, this risk should be contemplated across a range of possibilities including "irregular warfare scenarios, operations in austere or concealed settings, and other asymmetric environments, as well as conventional campaigns" [25]. This showed further development in the understanding of how energy costs, energy risks, capabilities, and even their connections are all functions of both the future operation engaged in and the military force used in those engagements. Both are uncertain and can dramatically differ from anything experienced recently or even ever. These differences might be caused by significant political or societal events that radically alter the probabilities of certain engagements, encouraging military reformation by connection, or force changing technology that can substantially alter combat tactics, logistic procedures, or both. This manual attempted to encourage appreciation of these connections and the uncertain possibilities of tomorrow.

The Department's support of the FBCE concept was further demonstrated when it published the 2010 Quadrennial Defense Report (QDR) in February. Within which, President Obama called on the DoD to fully implement the energy-related KPP and burdened energy metric required by the NDAA for FY2009. This document also introduced the term "energy security," which "means having assured access to reliable supplies of energy and the ability to protect and deliver sufficient energy to meet operational needs" [26]. This established energy security as a related but separate concept to energy as a force multiplier. It suggested a desire for

FBCE, or any energy metric, to help incentivize both energy efficiency and resilience in decisions.

In June 2010, AT&L introduced another efficiency initiative known as Better Buying Power (BBP) 1.0, which was shortly followed by guidance and implementation memoranda [27]–[29]. While it included many initiatives, BBP had the general objective of delivering the necessary warfighting capabilities within a declining defense budget. As a big-picture program, FBCE, or other particular energy metrics, was not directly mentioned. However, several of the initiatives (e.g., target affordability and control cost growth) discussed the importance of properly accounting for life-cycle and logistic support costs.

Under the responsibilities of the newly created OEPP, the first budget certification report for FY2012 was released in January 2011 and the first energy strategy in June 2011 [30], [31]. Given the timeline of the office's creation and report release dates, the first budget certification report evaluated Service initiatives each based on their own energy goals. While in general it found the service efforts to be adequate, the report also noted that:

> "Across the Department of Defense, we generally do not have a clear understanding of how energy is being consumed at the point of use and therefore, are unable to make well[-]informed resourcing decisions."
>
> "Energy costs are underestimated in analyses used to inform investment decisions across the Department in that assets and infrastructure used to move and deliver fuel are not included."
>
> "Operational energy concerns are not adequately addressed in force development modeling and simulation resulting in less than optimal and sometimes inadequately informed recommendations and tradeoffs" [30].

The first energy strategy attempted to align the visions of the 2010 QDR and the DoD. This report outlined three principal ways to adjust military energy usage: reduce demand in operations, expand and secure the supply, and directly plan for energy security in the future [31]. These would later become the three pillars for all DoD energy initiatives. All three of these approaches pointed to the unnecessary and suboptimal balance of energy-related cost and risk created by the then DoD decision-making practices. FBCE was directly mentioned as a means to more properly value energy into force development decisions [31].

To further help the goals established in their first energy strategy, OEPP partnered with Joint Staff J-4 to oversee further development of the Energy KPP within the JCIDS. This update became mandatory in January 2012 and incorporated FBCE as part of both the Energy and Sustainment KPP [32]. This refinement and then move to two KPPs again shows a growing understanding of the importance of FBCE within the DoD while simultaneously demonstrating a lack of consensus of how to calculate and where to put it.

That same year, the NDAAs for FY2011 and FY2012 continued to refine the recently created operational energy office. In January, the Ike Skelton NDAA for FY2011 changed the title of the head of OEPP to Assistant Secretary of Defense [33]. In December, The NDAA for FY2012 added a senior official for OEPP to the Joint Chiefs of Staff and Joint Staff, as well as codifying a definition for energy security similar to that presented in the 2010 QDR [34].

In March 2012, the DoD released the implementation plan for its first operational energy strategy. It highlighted seven targets, which included to "incorporate energy security considerations into requirements and acquisition" [35]. Around that same time, the Defense Operational Energy Board (DOEB) was established to "share operational energy lessons learned; improve and facilitate coordination of operational energy policies, plans and programs; [and] advocate for the integration of operational energy considerations into DoD Component processes" [36]. It was co-chaired by the Assistant Secretary of Defense for OEPP and Joint Staff Director of Logistics.

The next budget certification report, released in June 2012, again found service-level initiatives and plans adequately met energy goals but noted that:

> "the Department needs to develop and implement the tools and systems required to incorporate energy security considerations into Requirements and Acquisition. The Army has not budgeted for the sustainment and improvement of the "Sustain the Mission" modeling and simulation tool, which is a foundational tool for the Army to evaluate fuel logistics plans. Neither the Navy nor the Air Force has budgeted for the development of the modeling and simulation tools to enable force planners to simulate and assess the combat capability effects of enemy attacks on U.S. logistics forces" [37].

In July 2012, AT&L issued its most recent application guidance on FBCE methodology to inform trade decisions in Analysis of Alternatives (AoAs) and acquisition programs as well as to provide consistency between service calculations [38]. It specified that unlike other cost methods, FBCE is intended to be both scenario-dependent and account for apportioned delivery and protection costs.

That release was soon followed with additional guidance on the Energy KPP and a report entitled "Addressing Fuel Logistics in the Requirements and Acquisition Processes."[39] In that report, OEPP believed the established FCBE guidance would provide "a framework to incorporate costs associated with moving and protecting fuel into design processes for tomorrow's military equipment." This guidance was incorporated into the Defense Acquisition Guidebook (DAG) [40].

In November 2012, AT&L released guidance updating BBP. Again, while FBCE and other energy metrics are not directly mentioned, the memorandum stresses the importance of including properly determined sustainment costs and increased use of such analysis as Performance-Based Logistics though no direct implementation guidance is given.[41]

In January 2013, AT&L released a directive on contingency basing outside the United States. It clarified the role of operational energy and positive impacts of smaller logistic footprints [42].

When released in March 2013, the first operational energy annual report highlighted the efforts taken to incorporate FBCE into DoD practices. These included OEPP coordinated actions to include scenario-based analysis and the calculation of FBCE for each alternative at the AoA [43].

Besides reflecting the previously mentioned guidance, the latest version of the DAG, updated in May 2013, defines FBCE as

> "the energy-related costs to sustain specific pieces of equipment, including procurement of energy, the logistics needed to deliver it where and when needed, related infrastructure, and force protection for those logistics forces directly involved in energy delivery" [40]

The DAG goes on to explain that growing logistics footprints impede combat forces capabilities, create lucrative targets for enemies and necessitate escort support from otherwise frontline combat assets. In the same sense, reductions in energy demand can have beneficial affects to operational forces. These reductions can be achieved through "different, better informed tradespace choices, design alternatives, technologies, and force structure concepts" [40]. FBCE can "over time help DoD manage larger enterprise risks."

Then in June 2013 the Deputy Secretary of Defense released the “Deputy’s Management Action Group Guidance for a Comprehensive Defense Energy Policy.” In this memorandum, the Deputy highlighted that changes in the Department’s use of energy are needed to enhance military capability, improve energy security and mitigate costs [44].

Released later that year in September, the operational energy annual report for FY2012 emphasized the importance of the JCIDS updates as they help “limit growth in future system energy demand by ensuring that energy performance issues are captured, defined, and included in acquisition trade decisions” [45]. OEPP recognized that determining the impact of FBCE was difficult since “relatively few AoAs have been commissioned since the publication of the [FBCE] guidance.” However, gains were expected as this metric continued to be used in future decisions.

An interim release of DoDI 5000.02 in November 2013 moved FBCE from a separate section to include it within the AoA evaluation. The change required that proposals be evaluated in part by how well they "consider[ed] the fully burdened cost of energy (FBCE) where FBCE is a discriminator among alternatives" [46]. This may be one of the first signs of retreat for the energy metric’s support, where the instruction suggests its use as a component among otherwise indifferent options, rather than a parameter on par with others. It is not publicly available whether any of the few AoAs started since the guidance’s publication have used FBCE as a tiebreaker.

More recent reports continued to recognize the importance of including energy in decision processes and proposed various energy-related programs and plans but direct development of or reference to FBCE was mixed. For example, the 2014 QDR included long lists of energy initiatives and directly connected energy to capability (e.g., "energy improvements enhance range, endurance, and agility, particularly in the future security environment where logistics may be constrained"). Also, the FY2013 Operational Energy Annual Report, highlighted the DOEB's focus on implementation of current energy policy rather than the development of it [47], [48]. Respectively published in March and October 2014, neither of these documents made any mention of FBCE or other decision-making energy-metrics.

In April 2014, the Assistant Secretary of Defense for OEPP testified to the Senate Subcommittee on Readiness and Management Support. Within that testimony, she mentioned the value of the Energy KPP and coined a new concept energy supportability analysis (ESA). While not officially defined in any regulation at the time, the concept seemed similar to FBCE though not directly attached to acquisition decisions:

> "We are also working together to ensure operational energy supportability analysis is conducted during the Services' concept development, which provides a realistic energy distribution and allows simulated enemy forces to interdict our energy supplies, to more closely approximate real world conditions" [49].

Also in April, the office of the Under Secretary of Defense for AT&L published DOD Directive 4180.01, which discussed DoD energy policy and assigned responsibility for ESA and FBCE to different offices. A restatement of some previous reports, it established as DoD policy "that energy analyses are included in DoD requirements, acquisition, and planning, programming, budgeting, and execution (PPBE) processes". In accordance with DoDI 5000.02 and the DAG, the Director of Cost Assessment and Program Evaluation (DCAPE) would guide and assess FBCE analyses in "all developmental DoD systems with end items that create a demand for energy in the battlespace." Secretaries of the Military Departments would "support" and Chairman of the Joint Chiefs of Staff would "ensure joint planning that includes energy considerations and energy supportability analyses across the full range of military operations, from engagement and security cooperation to major operations and campaigns" [50]. This was the first indication that the metrics were not entirely overlapping. While they were both scenario-based tools used to incorporate burdened energy into decisions, one was designed for acquisition decisions, while the other operational planning.

In December of the year, the Carl Levin and Howard P. 'Buck' McKeon NDAA for FY2015 introduced another new concept to burdened logistics and made further changes to the office of OEPP. Section 316a required bulk purchases of drop-in fuels to be cost-competitive with the fully burdened cost (FBC) of traditional fuel, where FBC was defined as the FBCF was in the NDAA for FY2009 [51]. It also codified the repeal of the position of Assistant Secretary of Defense for OEPP and merged OEPP with the office for Installations and Environment.[52] The merged office was renamed Energy, Installations, and Environment (EI&E) and headed by an Assistant Secretary of Defense. OEPP was included as Operational Energy (OE).

The January 2015 update to DoDI 5000.02 kept FBCE as a part of the AoA procedures, where the DCAPE should use it a discriminator among alternatives [53].

A month later, the next JCIDS release removed FBCE from its previous role within the KPPs and replaced it with ESA; at the time adding some guidance to this relatively new concept. This document stated that using scenario-based analysis and "realistic threats and disruptions to those logistics," ESA should expose the relationships between energy supply and demand that were critical to highlight options that affordably managed energy, logistics, and risks without reducing capability [5].

In March of that year, the Assistant Secretary of Defense for the newly created office for EI&E gave a rough breakdown of operational energy expenditures to a Senate subcommittee. He explained that "[a]pproximately 92 percent of Department spending on operational energy initiatives focuses on reducing demand, while the remainder addresses energy supplies and adapting the future force" [54]. He also stated the office was working with Joint Staff J-4 to improve the guidance on ESA within the JCIDS Manual.

By May, EI&E released its first energy report since the merger of the offices and explained the perception of energy within the DoD. First and foremost, energy was seen as an enabler of military capability, the true appreciation of which required understanding energy availability and resilience. Second, energy was a significant expense; unnecessary usage took resources directly from both current and future military capability. To address these, EI&E tracked energy initiatives within three areas: expanding supply, reducing demand, and adapting future forces and technologies, with the vast majority of expenditures in reducing demand. The report went on to list initiatives, none of which discussed improving decision tools, such as ESA or FBCE [55].

Released this time by the Office of AT&L in June 2015, the FY2014 Operational Energy Annual Report highlighted some areas of progress in energy analysis. First, distributed in 2014, DoD Directive 4180.01 was the first overarching energy policy in over 20 years with an organization-wide framework. Second, the Operational Energy Capability Improvement Fund (OECIF) initiated six programs in FY2014 to address operational energy analysis and decision making throughout DoD's planning and requirements process. Third, it indicated that war gaming finally included energy constraints and opportunities [6]. FBCE and ESA were both mentioned though any understanding of the distinction is blurred. The need for further guidance on ESA was mentioned as part of the Energy KPP (i.e., acquisition process). FBCE was identified as a success story of energy initiatives but the supporting evidence directed the reader to a website being dismantled as a result of the merge with Installations and Environment in December of the prior year [56].

The preliminary release of the Operational Energy Certification of FY2016 Budget by EI&E pointed to caveated progress. It stated that the military was adapting analytical processes to consider operational energy, risk and capability, but more emphasis and funding on modeling and simulation tools was needed [57].

In one of its final releases, the office of OEPP identified some important operational energy considerations.

> "While remaining globally engaged, the Department's focus towards the Pacific means that the tyranny of distance is an even greater challenge to logistical support. Combined with adversary advances in Anti-Access and Area Denial (A2/AD) capabilities, this environment places logistical support, and specifically energy support, at risk" [4].

It went on to say that these risks should be considered throughout various decision processes via ESA. In accordance with the NDAA for FY2015, "ESA facilitates the identification of energy shortfalls and informs decisions on risk mitigation, such as changes in system design, the Concept of Operations (CONOPS), force structure, and procuring additional logistics." This analysis ensured the incorporation of logistic costs and risks by "focusing on systems nearing production or post-production" and helped suggest mitigation approaches (e.g., changes to tactics, techniques, and procedures or force structure) [4]. It is unclear if this is implying an adjustment in the perceived burdened energy metric gap. FBCE analysis was always intended to occur early in acquisition decisions and at a level unable to suggest force structure changes.

Later in September, former Assistant Secretary of Defense for Operational Energy, the Honorable Sharon Burke, recounted the motivation that led to the NDAA for FY2009 and creation of the first burdened energy metric in an interview. She said that while somewhat a function of high oil price, it was mostly recognition of the vulnerability of fuel convoys and supply lines in general. These vulnerabilities led to casualties and required the reallocation of combats to escort duties. In other words, the military wanted a way to both reduce energy costs while addressing the resource's dual nature (i.e., liability and opportunity). She explained this was not an issue eliminated by currently low energy costs:

> "In the Asia-Pacific theater, where much of our future lies, we must move a lot of fuel a very long way. Countries, and even non-countries, are going to have precision weapons, and the ability to hit our supply line[s]. We have to cut that vulnerability in the long term" [58].

The most critical steps throughout this history to the rise and fall of FBCE are shown in Figure 4.1.

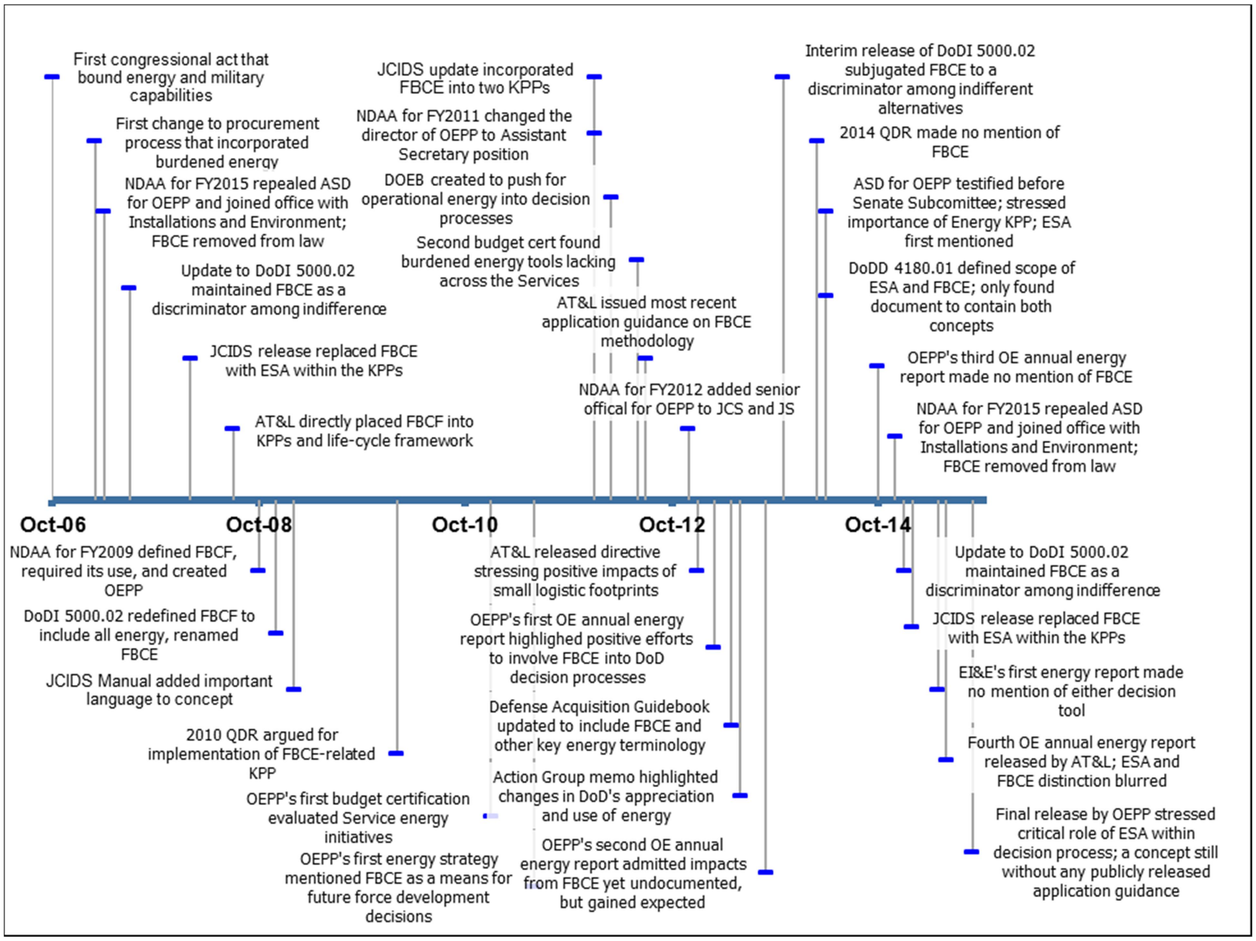

Figure 4.1: Timeline of DoD History

4.2.2 Within the Navy

This section contains an overview of the history of FBCE within the United States Navy (USN). Attempts to include logistic footprint in decisions within the Navy started before FBCE. For example, the 2004 release of the Secretary of the Navy Instruction (SECNAVINST) 5000.2C, Total Life Cycle Systems Management required program managers to “maintain system long-term readiness, increase reliability, and reduce the logistics footprint” [59]. However for the purposes of this work and because these early attempts did not focus specifically on energy, this history emphasizes efforts after the NDAA for FY2009.

As the history shows, budding interest in energy initially leads to attempts to incorporate FBCE into various decision-making processes. However, as was seen in the DoD, these efforts failed to find an application method for FBCE that was both widely accepted and properly highlighted all the aspects of burdened energy in tradespace analyses. The most recent evidence demonstrates an increased appreciation for energy without any clear indications of application attempts.

Following the NDAA for FY2009, the Navy's first Service-wide energy strategy was released in October 2009. The Secretary of the Navy (SECNAV) published a document entitled "Naval Energy: A Strategic Approach," where he outlined his vision for energy reform [60]. Echoing many DoD-level concerns, the SECNAV stated that:

> "The Department of Navy's current energy demand creates multiple vulnerabilities for tactical platforms. Ships, aircraft, and ground vehicles must frequently receive new supplies of fuel. At sea, ships are most vulnerable [when] alongside an oiler during underway replenishment. In the air, refueling costs are increased by an expensive logistics tail. On the ground, convoys of tanker trucks are magnets for insurgent attacks, putting lives at risk and drawing forces away from the fight" [60].

In response, he directed the USN to expand its operational capabilities, minimize risks, and save time, money, and lives through several energy initiatives including "adapt[ing] operational policies and doctrine to value energy as a strategic asset."

The strategy also outlined a structure to lead these initiatives, appointed the Naval Energy Office as principal advisor to this position, and coined the term "tactical energy security," predating the creation of "energy security" at the DoD level:

> "Tactical energy security is protection from vulnerabilities related to the energy requirements of tactical platforms by reducing risk associated with a logistics tail, volatile petroleum prices, and the instability of unfriendly petroleum suppliers" [60].

These initiatives were formalized into five goals presented on 14-15 October 2009 at the Naval Energy Forum in McLean, Virginia. These goals included adjusting the way the Navy and Marine Corps award contracts "to consider the lifetime energy cost of the system" [61]. This was reinstated at the end of the month with an energy awareness message from the SECNAV [62].

While momentum behind its intent was gaining ground, FBCE's application remained at the initial stages. At the end of 2009, presentations at a Military Operations Research Conference demonstrated Service use of the calculation method released by AT&L [16], [63]. It was at least another year before the Navy released any information on Service-specific application attempts. A summary of these attempts is included in a previous work [64].

In October 2010, the Navy published an energy vision describing the impact of energy on several important factors and recognized the value of FBCE.

> "Beyond the strategic significance of energy, the energy demands of individual Navy systems create constraints at the operational and tactical levels. Being wedded to liquid fuel is a concern for every Sailor whose options in the battlespace are limited by the range and endurance of his or her ship, aircraft, or tactical vehicle. Moreover, the need to provide fuel to tactical forces requires a long and often vulnerable logistics tail, which draws forces from the fight and exposes support units to hostile action. These additional requirements of securing and transporting fuel to tactical forces effectively increase the overall cost of fuel. This true, delivered price is now called the 'fully-burdened cost of fuel.' Although fuel constraints will not be eliminated entirely, targeted investments in energy efficiency lengthen the fuel tether, enhance combat capability, and provide more options to Navy and Joint Force commanders" [65].

In this vision, the Navy also recognized the vulnerabilities of fuel reliance, the long time horizon of system acquisition, and the need to improve various decision processes.

> "Federal, DOD, and Navy mandates now emphasize energy-related specifications in evaluating new systems afloat and ashore. The Navy will develop and implement an energy key performance parameter and energy figure of merit to guide these evaluations. In addition, the Navy has joined other Services and DOD in efforts to define and

> incorporate a fully burdened cost of fuel, which accounts for the total cost of purchasing and supplying fuel to different deployed platforms" [65].

To encourage these changes, the Navy released a strategic roadmap, which further demonstrated their commitment to incorporating FBCE into several decision processes, adjusted the previously established energy related organization structure, and recognized the need to change many current practices. The roadmap stated:

> "SECNAV is committing DON to transforming its requirements-setting, acquisition, and contracting processes to incorporate energy efficiency into decisions for new systems and buildings. DON will make energy a consideration in new contract awards and consider the overall energy footprint of contractors as part of the acquisition process. For tactical systems, the Navy and Marine Corps will incorporate the fully burdened cost of fuel (FBCF) methodology in determining life[-]cycle energy costs, and set the energy demand of new systems with an operational energy Key Performance Parameter (eKPP) to optimize operational effectiveness and limit fuel logistics impacts" [66].

Adjusting previous guidance, the Assistant Secretary of the Navy for Research, Development, and Acquisition (ASN(RD&A)) was to ensure that DON Research, Development, Test and Evaluation (RDT&E) and Deputy Assistant Secretary of the Navy (DASN) Energy supported the energy goals of the SECNAV. The office was also in charge of developing implementation guidance for the goal to make energy an evaluation factor in DON contracts. Finally, to properly instill FBCE and "institutionalize behavioral change among every Sailor, Marine, and DON civilian employee," the roadmap recognized the need to adjust current doctrine, policy and guidance by "changing acquisition and contracting practices, operational methodologies, training routines, and installation energy management practices" as well as collecting data to better inform decision makers at all levels [66].

The first attempt to incorporate energy as an acquisition evaluation factor was released in June 2011. The memorandum provided guidance on the use of energy-related factors in acquisition planning and trade-off analysis and was the first Service level memorandum to use the term "FBCE" [67]. This document was broken into five areas.

In the first, ASN(RD&A) specifically tasked the four System Commands (SYSCOMS), Naval Sea Systems Command (NAVSEA), Naval Air Systems Command (NAVAIR), Marine Corps System Command (MARCORPS), and Space and Naval Warfare Command (SPAWAR). The SYSCOMS were to "develop a uniform method for calculating FBCE: NAVSEA for on and undersea platforms, NAVAIR for all aviation platforms, MARCORPS for terrestrial, and SPAWAR for non-platform, energy consuming systems" by October 2011. At a minimum, these methods were to include

> "(i) a standard commodity cost; (ii) operating service-owned fuel delivery assets costs, including personnel costs, that are required for resupply; (iii) force protection; (iv) depreciation costs of fuel delivery and force protection/convoy assets."

They also had to be tied to AoA scenarios and address both steady-state and surge Operational Tempo (OPTEMPO). This section also stated that all program cost estimates generated by the Naval Center for Cost Analysis and SYSCOM Cost Estimating directorates "shall consider" FBCE. The second section built off of affordability targets issued by AT&L in a memorandum from 2010 [28]. It stated that affordability targets should be use FBCE costs while Service cost position should use standard fuel cost. The third required that many acquisition programs involving energy-consuming end items consider energy as an evaluation factor, not sub-factor, and include alternatives, trade-offs, and risks in the discussion of FBCE [68], [69]. The last two sections discussed changes to energy consideration in the Gate Review Process for new and legacy systems. While FBCE was not directly mentioned, these sections did stress several import energy-related considerations (e.g., the value of reducing energy requirements, especially in combat) [67].

In September 2011, SECNAVINST 5000.2E was released, incorporating DoD-level changes into Navy practices, including adjustments to FBCE.

> "AoAs shall consider alternative ways for tactical systems to improve energy efficiency and also consider the fully burdened cost of energy in conducting trade-off analyses for all tactical systems that create a demand for energy" [70].

Between September and November 2011, the Chief of Naval Operations Energy and Environmental Readiness Division created the Navy Operational Energy in Acquisition Team (EN-ACQT) to ensure energy-related factors were incorporated into decisions at system development and acquisition [71], [72]. No public record of EN-ACQT's successes related to FBCE or similar energy metrics could be found.

Released in March 2012, SECNAVINST 4101.3 demonstrated further development of the energy discussion within the Navy and assigned responsibilities across the Service for DON energy programs to meet requirements created by the Energy Evaluation Factors in the Acquisition Process memorandum. The Assistant Secretary of the Navy for Energy, Installations, and Environment (ASN(EI&E)) was charged with leading the effort and approving all energy metrics. DASN (Energy) was named as the primary executor for energy programs, policies, and initiatives, which included developing a strategic energy plan and annual guidance though these don't seem to be publicly available either. This annual guidance was intended to inform the necessary data collection and other metric requirements. DASN (Energy) was also to cooperate with ASN(RD&A) to help develop FBCE calculation methods within the SYSCOMS. In addition to cooperating with DASN (Energy), ASN(RD&A) was tasked to coordinate with the appropriate authorities to implement energy requirements (e.g., Energy KPP in the JCIDS). This effort would be assisted by the Chief of Naval Operations (CNO) and Commandant of the Marine Corps (CMC).

In June 2012, ASN(RD&A) released a follow-up for the energy evaluation factors memorandum. It stated that all SYSCOMS met the tasking of the previous memorandum. Additionally, the office approved all of the presented methods and said they should be used in future programs [73]. While the other SYSCOM's approved FBCE calculation methods were not publicly released, Dr. Doerry published a technical paper outlining the approach of NAVSEA in the third quarter of 2013 [74]. In response to the ASN (RDA)'s 2011 memorandum, NAVSEA developed a Design Data Sheet (DDS). DDS 200-2 was released in 2012 and estimated the fuel consumed by a surface ship for each year it is in service [75]. Translating this to FBCE requires assumption of a lifetime of operation scenarios based on a 2007 Navy Report, breaking those scenarios into ship states, and aligning those ship states with electric loads and fuel burn rates [76]–[78]. This marked the peak of application attempts in the Navy.

A presentation by DASN (Energy) in 2012 summarized Navy energy consumption and efforts to meet SECNAV goals. Similar to the rest of the DoD, the Navy used about 75% of its energy to support tactical operations, while the remaining 25% supported shore activities in 2012. However, the percent distribution of energy sources was noticeably different than DoD averages, mostly due to the prevalence of nuclear powered ships. The presentation failed to mention any work on energy metrics or decision-making tools [79].

In September 2013, the third and most recent update to the energy evaluation factors in acquisition process memorandum was released. It reminded acquisition decision makers that certain programs must consider energy in tradeoff choices as an evaluation factor, not sub-factor. No additional guidance on any specific energy metric was included [80].

The most recent view of efforts within the Navy to improve decision makers' perception of energy by outside agencies has been mixed. The Operational Energy Annual Report for FY2013 noted:

> "each of the Military Departments and the National Defense University instituted programs to integrate operational energy considerations into professional military education. For example, the SECNAV Executive Energy Series reaches the Navy's most influential senior leaders and shapes discussion of increasing capabilities…reducing vulnerabilities associated with energy requirements and consumption. In FY 2013, the first two courses were held with Flag, Senior Executive Service, and Senior Enlisted leader attendees" [48].

However, the Operational Energy Annual Report for FY2014 mentioned limited investment in important modeling and simulation tools, such as the Navy's Synthetic Theater Operations Research Model (STORM) as a concern. If properly funded, STORM and other such tools could "inform energy tradeoffs in requirements development and acquisition program performance criteria" [6].

4.2.3 Within the Marine Corps

This section contains an overview of the history of FBCE specific to the U.S. Marine Corps (USMC). It should be noted that this work found no use of that particular term in any USMC documents, except when referencing DON or DoD directives that used it. In addition, within USMC publications, the term "metric" is used usually to refer to a quantifiable measure used to track, monitor and assess success or failure, sometimes to the units of that measure, and a few times to both; clarification is provided when necessary.

Marine Corps history follows a similar path to that seen at higher levels. In the beginning, a similar interest in energy initially results in efforts to find a place for FBCE in various decision-making processes. However, as before, these efforts failed to find an application method for FBCE that was both widely accepted and properly highlighted all the aspects of burdened energy in tradespace analyses. The most recent experience confirms past experience.

In November of 2009, the Assistant Commandant of the USMC recognized energy as a priority by establishing the Marine Corps Expeditionary Energy Office (E2O). The E2O's mission was to "analyze, develop, and direct the Marine Corps' energy strategy in order to optimize expeditionary capabilities across all warfighting functions" [81]. Furthermore, E2O's role is to "advise the Marine Requirements Oversight Council (MROC) on all energy and resource related requirements, acquisitions, and programmatic decisions."

Also that year, the 35th Commandant of the Marine Corps sent out his planning guidance. While ordering improvements in many areas, the Commandant recognized the importance of energy in his second priority and directed E2O to focus on the following three areas: increase renewable energy, create a culture of energy efficiency, and improve the efficiency of equipment [82]. While not highlighting any work on burdened energy-related metrics, this demonstrated a growing appreciation of the direct connection between energy and capabilities.

In early 2011, the USMC released their own energy strategy and implementation plan, which with their vision and strategic roadmap, identified the Corps specific motivations, goals, and responsibilities for adjusting energy employment on the battlefield and other decision processes [83], [84]. This effort was motivated by the dramatic increase in fuel requirements caused by an alarming increase in the number, weight, and energy requirements of deployed systems (e.g., a Marine Infantry company in 2011 used more fuel than an entire battalion in 2001 and carried 2.5 times more radios and 3 times more data systems). The document stressed the connections between capability, logistics, and energy, directed that energy efficiency be made a priority in capabilities specified in Marine Corps Order (MCO) 3900.15B [85], and introduced a graphic illustrating the connection between energy and capability and the potential overlapping solution space:

The plan also recognized the difficulty of creating a useful energy metric:

> "The most useful metric would be gallons of fuel expended for a particular, standardized military objective. However, we currently lack this insight—detailed operational energy data is not routinely collected and reported within the Marine Corps on the battlefield or in training" [83].

At that time, the Corps only had aggregate energy and deployment data, which it used to determine that the USMC was consuming about 8 gallons of fuel per marine per day. It concluded with a reminder of the Corps' commitment to finding a way to integrate energy into decision making:

> "We will integrate energy efficiency and energy performance criteria as a requirement and a key evaluation factor for our equipment, vehicles, and weapons systems during source selection, where practicable. We will consider energy performance in the same trade space as cost, schedule, and performance" [83].

In September 2011, the USMC released version one of the Initial Capabilities Document (ICD) for Marine Corps Expeditionary Energy, Water, and Waste (E2W2). Another piece of the previously discussed USMC energy plan, the document described energy capabilities, gaps, and proposed solutions that supported Marines across a range of military operations stating, "Events of today and projections of the future require Marine forces to operate in widely varying, hostile, often access-denied, environments across extended battlefields" [86].

The report analyzed three scenarios: Major Combat Operations, Irregular Warfare, and Humanitarian Assistance/Disaster Relief. All the scenarios assumed unopposed sea-dominance and sea-based logistic support [86]. This showed the growing understanding of the critical connections between energy and capabilities, which are functions of an uncertain future. Properly designed metrics must account for these uncertain relationships and factors. Though the range of futures considered were fairly narrow, the report also recognized fuel considerations in planning and operations as part of several priority gaps. It suggested a list of non-materiel solutions at various levels (e.g., policy, doctrine, organization, leadership) including publishing "guidance on applying energy considerations to acquisition life[-]cycle cost estimates" and establishing "policy for energy as a risk factor in planning" [86].

In the beginning of 2012, the USMC released a science and technology strategy plan. As the name suggests, this document highlighted the focus on materiel developments that reduced logistic footprints and did not mention FBCE or any other decision metrics [87].

In September, E2O, released a report on their data collection efforts.[15] This was the result of an endeavor started by an Experimental Forward Operating Base (ExFOB) in Quantico, Virginia and formalized by a charter released in March 2012 [88]. While the report never discussed its possible connection to decision metrics, this data aided efforts to address inappropriately sized deployed power systems in Afghanistan [89].

An updated version of the ICD for USMC E2W2 also released in September further demonstrated the development of energy considerations into various decision processes. For the

[15] E2O was the office created by the CMC in 2009.

purposes of this history, the analysis and conclusions were similar enough to the initial release to skip recounting though this document did demonstrate a desire for guidance on acquisition energy considerations that continued until late 2012 [90].

Launched in 2013, the Commander's Energy Readiness Program (CERP) attempted to use data to maximize capability within an environment of declining budgets and limited energy resources. Similar to the ExFOB program, CERP is focused on operation decision makers [91].

Distributed in May 2013, MCO 3900.19 attempted to assist acquisition decisions by defining energy performance considerations early in development and furthered the motivation and efforts first espoused in the 2009 strategy and implementation plan. It connected energy to the capabilities of, and risk absorbed by, Marine Corps units and highlighted some externalities within the current logistic system, stating:

> "This increase in demand for 'liquid logistics' constrains operations, places a significant risk and strain on the distribution pipeline, and increases the overall weight of the Marine Air Ground Task Force (MAGTF)…Energy is the only combat enabler that crosses all elements of the MAGTF, from our aircraft to our individual Marines, on every mission and movement. The challenge with capturing energy in our requirements and acquisitions processes is that most energy consumers often are not responsible for the energy they use and those that supply energy have no controls over consumers" [92].

This MCO formally replaced energy efficiency with the term "energy performance (EP)" and defined it as:

> "The rate of energy consumption or energy harvesting required to perform a specific function or task in a specific operational mode, mission profile, and environmental condition. EP applies to any capability or system that converts energy into work or from one form to another, stores energy, transfers energy, or consumes energy."

The MCO included a guide entitled "U.S. Marine Corps Energy Performance Requirements Guide for Capability Development." This guide defines the EP KPP as:

> "A metric, with measures, for a system or system of systems (SoS) EP attribute that is deemed critical or essential to the development of an effective military capability, or for which energy performance improvements would enhance individual, unit, or MAGTF combat effectiveness. EP attributes apply to any system whose primary mission includes energy harvesting, conversion, storage, transfer, or consumption. The EP KPP may require supporting attributes or Key System Attributes (KSAs) and must be technically feasible and quantifiable for test purposes" [92].

The guide states that several metrics, meaning units, may be necessary to properly define this KPP and other energy-related KPPs and KSAs. These metrics are in turn explored through modeling with the example of MAGTF Power and Energy Model (MPEM). The guide also suggests training and metric analysis tailored to the location of the system within the energy chain (e.g., production, storage, transfer or consumption). While it is not specifically listed in the MCO or guide, FBCE's common units are included (e.g., gallons per day, gallons per hour, and pound of fuel per flight hour) [92].

MCO 3900.19 was significant enough to draw the attention of OEPP in their Operational Energy Annual Report for FY2013. It was viewed as a significant success that the USMC was attempting to not just maintain but increase combat effectiveness by directing "the integration of energy performance metrics and measures into all applicable materiel capabilities" [48]. Without question, MCO 3900.19 illustrated a continued interest in understanding the first-order energy for the purpose of improving capability. However, it also lacked any language demonstrating this interest extended into the challenge of forecasting burdened energy and understanding its connection to capability.

4.3 Conclusions

From the outside, the results of all these efforts are mixed at best. At the DoD level, an office focused on operational energy was created than repositioned within another. FBCE was created, additional guidance released, and its priority within decisions elevated before it was seemingly subjugated to decisions of otherwise indifference and then potentially replaced by ESA, a metric with no publically released application guidance. Any success stories or even the use of either metric are not publicly available. Additionally, any impacts they have had or might have on tactics, planning, or procurement is indiscernible at this time.

What is clearer is that the appreciation of energy's cost, risk, and impact on capability has grown as well as the willingness to try to incorporate it into decision processes though execution remains far short of either. With the withdrawal of most of the forces from the long supply lines of Afghanistan and budget reductions, the impetus to continue this reform may be reduced along with the resources to support it. However, given the inevitability of some military operation in the future, uncertainty of what exactly that may be, tightening defense budgets, force changing technology on the horizon (e.g., unmanned combat and logistic systems and direct energy weapons) and gaps in current analysis tools, this is the perfect time to continue reforming many defense decision processes and finally designing a burdened energy metric that works.

More importantly, the DoN has noticeably slowed releases of new or updated energy-related initiatives, procedures, and guidebooks. This could be related to a number of factors, such as withdrawing from Afghanistan, falling energy prices, decreasing Service budgets, decelerating DoD and/or Federal level interest. It may also just be a false perception based on publicly released documentation as work continues quietly within the Service. However, based on what is available, it is clear that the issue that FBCE was originally designed to help mitigate is conceptually much better understood but there is still a great deal of work needed to properly quantify and communicate that understanding to decision makers. As the United States military prepares to face its next challenge in a sea of uncertainty and tightening budgets, this is precisely the time to improve those decision making tools.

For the USMC, what may have started as a way to satisfy the SECNAV's goals, efforts within the USMC to incorporate energy factors into various decision processes accelerated quickly. It is difficult from the outside to know how effective this effort was at encouraging real change within the organization but the externally visible signs are promising. After the USMC leadership adjusted the conversation on energy concerns from a "green-ing" force to one with a direct role in the capability space, even slowing progress at higher organizational levels left less impact on progress in the USMC. However, there is still an apparent decline in the rate of energy-related initiatives, procedures, and guidebooks released in the past few years and still no evidence of successful application. Even during its heyday, the unique direction of the Marine Corps leaves concerns. Based on publicly available documentation, the Corps' understanding of and application efforts for energy seemed almost entirely focused on first-order considerations. While mentioned sporadically, there is not as much evidence as at the other levels of an appreciation for burdened energy and its connection to capability, supporting non-material solutions to improve understanding of it, and finding ways to translate that decision makers. As noted at the DoD and DON levels, hopefully this is just perception as tools to aid decision makers on the connection between energy and capability are more critical than ever.

It needs to be also noted that at all of these organizational levels, focused and detailed analysis by stakeholders and the research community has to happen before potentially beneficial tradeoffs can be examined and is, therefore, both essential and warranted. In other words, the success of FBCE or any energy metric is highly dependent on sustained support from senior military officials and above not only during implementation but through its entire use [93], [94]. Some of the costs, risks and consequences of failing to properly incorporate energy and the sometimes complex ways it is connected to capability can be found in the other chapters. Chapters 5 and 6 also include recommendations for moving the conversation and analysis forward.

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Chapter 5: Learning from History: Finding a Better Way to Include Burdened Energy in Decisions

Abstract

This chapter adds value to the work by first, expanding on the example from Chapter 3 to include uncertainty and second, providing a demonstration of the framework outlined in Chapter 2 that incorporates capability. The first provides additional justification for the critical importance of uncertainty in decision-making involving energy, generally, and FBCE, specifically. The second illustrates the flexibility of the framework by applying it to a dramatically different example and incorporating a dimension of the tradespace vitally important to many military decision makers.

Logistics sets the campaign's operational limits. The lead time needed to arrange logistics support and resolve logistics concerns requires continuous integration of logistic considerations into the operational planning process. This is especially critical when available planning time is short [1].

Joint Pub 1, Joint Warfare of the U.S. Armed Forces, November 1991

The essence of flexibility is in the mind of the commander; the substance of flexibility is in logistics [1].

Rear Admiral Henry Eccles, U.S. Navy

5.1 Motivation

The United States DoD consumes a tremendous amount of petroleum products on operations powering its portfolio of air, sea, and ground vehicles, as well as providing energy services to stationary and mobile groups of personnel. This dependence on petroleum-based fuels and sensitivity to market price uncertainty create a significant risk to the organization, which at the very least can lead to short-term disruptions [2].

The commodity cost of energy is arguably the least important component of the total cost of energy for many decision makers in the DoD. Energy has several first-order impacts on the operational capabilities of any system. Tactical systems that demand more energy create larger or more frequent resupply requirements that increase the probability and consequence of interdiction and energy disruption. Some historic examples showing capability consequences and other costs of using metrics that fail to incorporate energy in all its dimensions into decision processes or do so poorly were highlighted in Chapters 2 and 3.

Qualitatively, these risks are understood. Originally known as Fully Burdened Cost of Fuel, the DoD created a metric in 2007 now known as Fully Burdened Cost of Energy (FBCE) to better value these hidden costs during the acquisition process.

Originally, FBCE was embraced by all DoD Service Branches. Anecdotally, support for FBCE has waned significantly since 2012. A detailed examination of the development of this concept in the DoD and DoN can be found in Chapter 4

Accordingly, there remains a need for a DoD-wide method that properly highlights the true cost and risks of energy reliance in acquisition decisions across a range of future possibilities. First, this chapter expands on the example from Chapter 3 to include uncertainty. This provides additional justification for the critical importance of uncertainty in decision-making involving energy in general and FBCE in particular. Second, it provides a demonstration of the framework outlined in Chapter 2 that incorporates capability. This illustrates the flexibility of the framework by applying it to a dramatically different example and incorporating a dimension of the tradespace vitally important to many military decision makers.

5.2 The Importance of Uncertainty

To demonstrate how uncertainty might impact decision makers, we return to the previously discussed case involving Guadalcanal. The previous analysis of the Tokyo Express resulted in different fuel per soldier cost estimates as the size of the convoy, number and type of escorts, and origin location varied. For this example, the soldiers per resupply destroyer is assumed outside the control of this decision maker, potentially because of such considerations as soldier availability and time restrictions, so the previously described distribution is incorporated. However, resupply convoy size and number and type of escorts is controlled and, as such, is analyzed parametrically. The resulting fuel per soldier estimates are shown in Figure 5.1 and Figure 5.2. The estimates are depicted in a box plot form with the median value displayed as the center line, box outlining the 25th and 75th percentile range, whiskers out to the 5th and 95th

percentiles, and mean value as an "+".The number of resupply destroyers and escorts are displayed as

$$X \text{ DD } (Y/Z)$$

where X is the number of resupply destroyers, Y is the number of escort destroyers, and Z is the number of escort heavy cruisers.

At first glance, if based entirely on fuel per soldier, these figures appear to present additional information superfluous to a decision maker; the rank order of preference based on mean estimates is equivalent to that based on mean or the amount of spread (e.g., uncertainty). However, there are several valuable insights shown even at this point that could be important to planners and other decision makers. First, while the spread grows roughly in proportion with expected fuel per soldier, it does so disproportionally above the mean. Accordingly, as operational decisions makers choose or are forced to resupply from farther distances and/or with more escorts, logistic decision makers need to adjust their decisions and plans need to account for the fact that the actual energy demands of the same unit of capability may occur over an increasing range. This can impact future capability either directly by unplanned shortages or by requiring operations to subside until proper reserves are stored to help mitigate this risk. Second, these figures show that the increases in energy per unit of capability are non-linear across the parametric analysis. For example, the increase in energy demand from a 3-ship unescorted resupply convoy from Rabaul to a 3-ship escorted resupply convoy from Truk is not equal to the sum of those changes (e.g., super-additive). This is true for both the expected energy demand and the amount of spread. As before, this stresses the need to better understand the connection between energy demand, cost, and capability and the importance of incorporating it properly into various decisions processes.

Next, we expand the analysis to include the possibility of mission failure and assign a benefit to escorts. For this example, mission failure is modeled at the vessel level and defined as any random event (e.g., mechanical issues, environmental circumstances, or enemy interdictions) that forces a vessel to return to a safe port without accomplishing its objective. Impacted resupply destroyers consume the fuel required for the trip without delivering their soldiers. Impacted escort vessels consume the fuel required for the trip without any estimated benefit to the convoy. Based on historic data for this campaign and others, it is assumed that the probability of a single vessel failure is a function of convoy size and modeled logarithmically (e.g., the regression exhibits marginal decay so a 6-ship convoy has a higher chance of having one failure but significantly less than twice that of a 3-ship convoy) [3], [4]. For resupply vessels, this is modeled with the following equation:

$$Probability\ of\ Single\ Failure = c_1 * \ln(\#\ of\ Resupply\ Vessels) + c_2 \qquad \textbf{5.1}$$

where c_1 and c_2 are coefficients chosen to conservatively model available data from Guadalcanal.

For resupply vessels, the possibility of mission failure decreases when escorts are used. Heavy cruisers are assumed to reduce the chances of failure more than escorting destroyers. The marginal benefit of multiple escorts also decreases logarithmically. While beneficial to the resupply convoy, the use of escorts creates the chance for escort mission failure, which is modeled with a similar equation. Dedicated escorts are assumed to be less susceptible to mission failure with heavy cruiser escorts being even less so than destroyer escorts.

This is intended to be merely illustrative. As such, parameters and regressions are chosen to conservatively follow the general trends of this campaign. Accordingly, the impact to the figures should illustrate the importance of accounting for these kinds of relationships even if the modeled failure/loss rate and escort benefit are different than those historically encountered during the Guadalcanal campaign.

Figure 5.3 and Figure 5.4 show the fuel per soldier box plots across the same resupply options with the possibility of mission failure and escort benefits included in the Monte Carlo analysis.

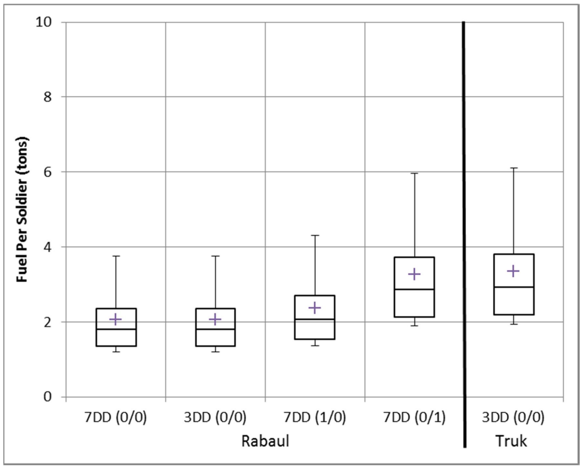

Figure 5.1: Fuel per Soldier without Losses (1 of 2)

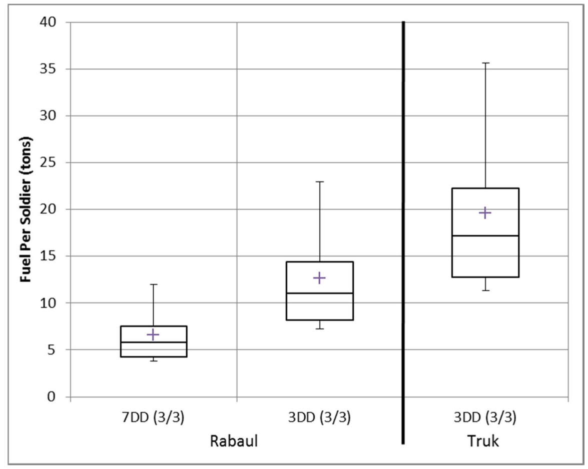

Figure 5.2: Fuel per Soldier without Losses (2 of 2)

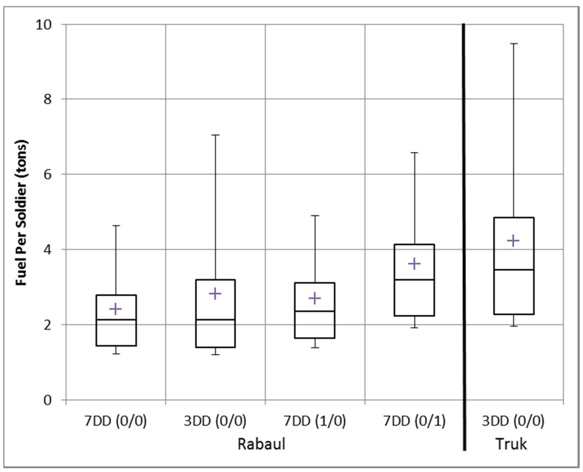

Figure 5.3: Fuel per Soldier with Losses (1 of 2)

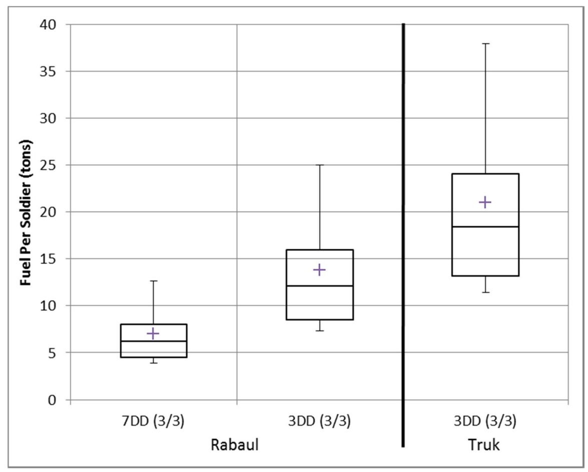

Figure 5.4: Fuel per Soldier with Losses (2 of 2)

By just adding these few features, Figure 5.3 and Figure 5.4 dramatically alter the decision space. First, there is a clear preference now between large and small convoys, both in expected cost and, very significantly, in the spread. Additionally, as expected, there is a definite benefit to escorts. This creates a clear preference between small, unescorted convoys and larger, lightly escorted convoys, which have a lower expected energy cost and less uncertainty. Interestingly, these relationships have lowered the correlation between uncertainty and expected value and, as a result, created options without obvious preference. For example, the 7-ship convoy from Rabaul escorted by a heavy cruiser has a higher expected cost but with less uncertainty than the 3-ship unescorted convoy from the same location. Given the risk-aversion of the decision maker or the organization, the benefits of reducing the uncertainty may outweigh the higher expected costs.

5.3 New Framework Applied and Discussion

This section is illustratively applies the framework from Chapter 2 to the Guadalcanal example from Chapter 3. For this motivational work example, capability is incorporated into the decision space by distilling the value of vessels involved down to their ability to support the delivery of soldiers. This is an intentionally incremental step from current FBCE designs. While important, military capability is itself multi-dimensional for most systems even in a single operation. Generalizing that across a range of systems used in a spectrum of environments against an uncertain opponent to accomplish a range of objectives requires a more flexible metric. That next step is the focus of Chapter 6.

In this example, the impact of the convoy structure used is analyzed as the rest of the scenario is held constant. As mentioned, destroyer convoys had flexibility in tactical deployment, which at the same time reduced escort requirements but created large fuel demands. Transport vessels required the allocation and coordination of larger convoys but could transport men and equipment more efficiently. In the figures below, FBCE Ratio, Equation 2.1, is plotted across low to high fuel demand and risk.

In Guadalcanal, the destroyers and transport vessels are assumed to originate from the same port without any other differentiating factors to their logistic upstream. However, the delivery vessels themselves and their associated escort requirements create different marginal changes to total fuel given the nonlinear increases in consumption and uncertainty of that consumption. In a similar sense, the marginal impact to risk is nonlinear. Using destroyers reduces time enroute to suffer from environmental events or interdiction attempts, lessens the actionable value and quality of opponent intelligence, and decreases escort requirements mitigating coordination requirements and uncertain event occurrence for those vessels. The sum of these factors nonlinearly impacts the expected risk and uncertainty of that risk.

In Figure 5.5, the two resupply systems are mapped per mission in the FBCE Ratio solution space. Point locations represent the expected mean FBCE Ratio. The circles surrounding each represent the standard deviation used to denote the relative levels of uncertainty for each dimension. As shown, both systems have similar levels of risk and fuel demand correlation because of the analysis boundaries. As seen, destroyers have the lower expected FBCE Ratio per mission. Given the sensitivity of FBCE Ratio to risk, the contributions to either supply method's FBCE Ratio distribution from each unit of risk and fuel demand are not equal. While it is based on the previous analysis, the relative position of the two systems is not critical at this point. Per mission, destroyer resupply creates less fuel demand and requires less risk with less uncertainty in both dimensions. This is more readily apparent when comparing the cumulative distribution functions (CDFs).

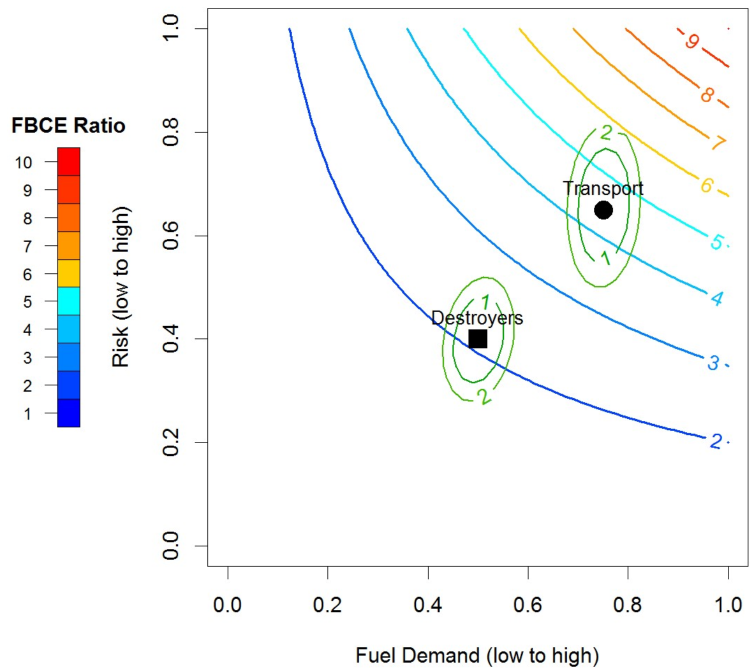

Figure 5.5: FBCE Ratio Solution Space Per Mission

Figure 5.6 shows the CDFs for these two systems assuming log normal distributions for the two resupply options. Because of the analysis boundaries and assumptions, destroyer resupply stochastically dominates transport vessel resupply per mission. Given this information, a decision maker's choice is obvious if no other consideration factors exist. However, one such critical factor currently excluded from this mapping is capability.

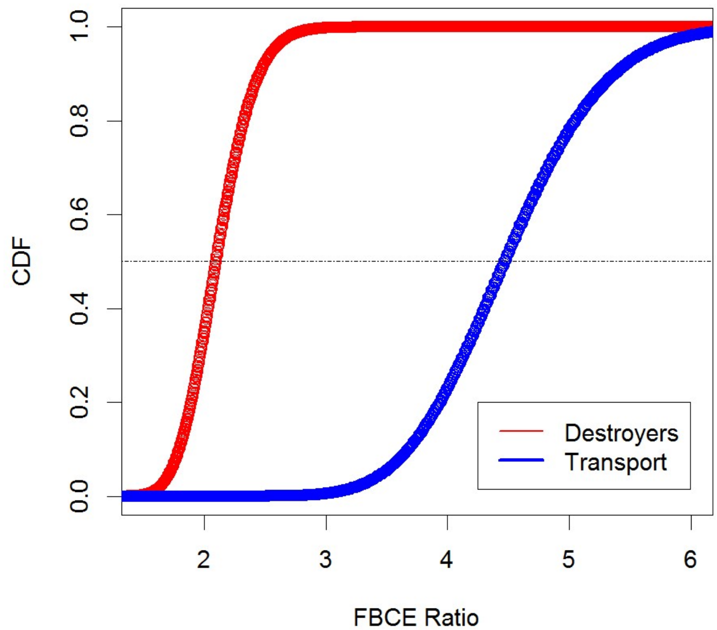

Figure 5.6: FBCE Ratio CDF Per Mission

Figure 5.7 shows the FBCE Ratio mapping after accounting for the soldier capacity of each resupply method. While it doesn't completely encapsulate all the capabilities of either system, especially the destroyers, per soldier analysis is a useful starting point given the role both systems played in this particular campaign for the Imperial Japanese Navy. As previously shown, the per soldier fuel demand for the transport resupply drops dramatically relative to the destroyer option. However, the transport resupply still suffers from higher and more uncertain risk (e.g., larger convoys, more complex operations, and longer transit times).

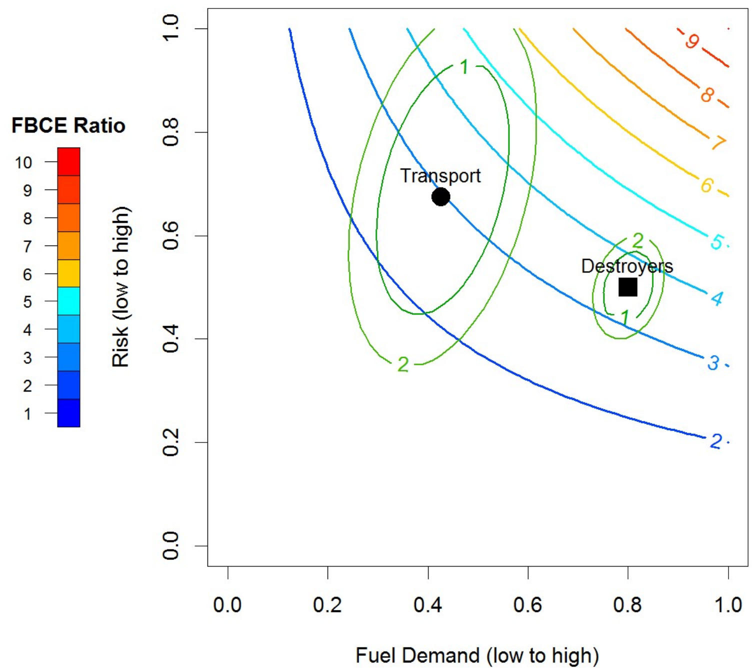

Figure 5.7: FBCE Ratio Solution Space Per Soldier

Figure 5.8 shows the CDFs for the per soldier mapping. At this point, transport resupply has a FBCE Ratio distribution with a slightly lower expected FBCE Ratio but with noticeable higher uncertainty. Now, the choice is no longer apparent and requires the decision maker to quantify organization risk aversion or qualitatively weigh the value of lower expected resource consumption versus the value of lower uncertainty in that resource consumption per unit of capability.

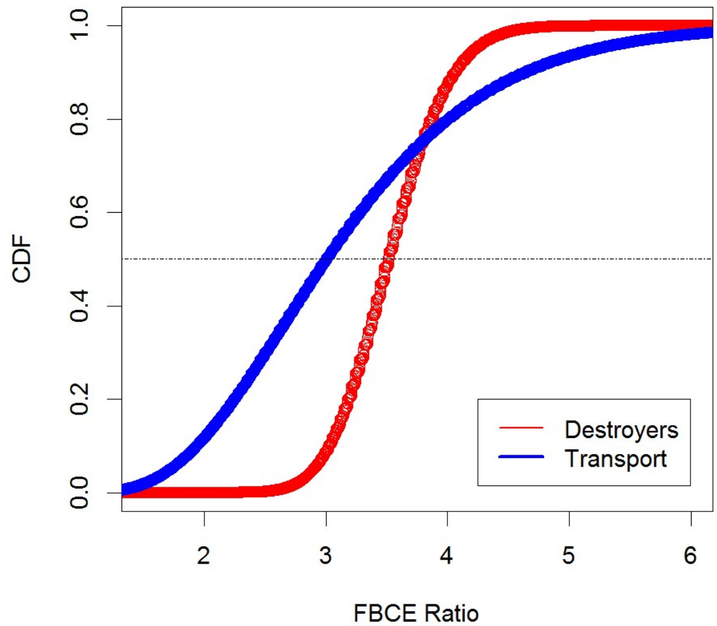

Figure 5.8: FBCE Ratio CDF Per Soldier

Taking this one step further, Figure 5.9 shows the FBCE Ratio per soldier mapping after attempting to appreciate each resupply option's ability to impact the opponent's capabilities and FBCE Ratio space. This necessitates further forecasting and requires additional but unequal uncertainty for both options. Because of reasons previously discussed, the resupply options had different probabilities of impacting opponent forces. This could significantly alter the energy cost and uncertainty required per unit of capability if it occurred. For example, the 13-14 October bombardment of Henderson Field required the assumption of additional risk and the investment of additional energy. However, in planning, this created the possibility, which might grow with sustained commitment, to directly destroy or incapacitate enough American aircraft and vessels to impact their campaign capabilities for a window of time. In other words, the transport vessels' escorts had the possibility to dramatically impact the America forces capability and cost to interdict Japanese resupply convoys and to conduct their own resupply. For the Japanese, the net effect of these factors meant the possibility of dramatically lower energy costs per delivered soldier and significantly higher capability per soldier. The destroyer resupply usually attempted to conduct runs without notice and had almost no discernible chance of directly impacting American capabilities. The impact to the mapping is illustrated in Figure 5.13. This figure shows the significant shift in both the expected position and uncertainty of that position for the transport option, while the destroyer option remains largely unchanged.

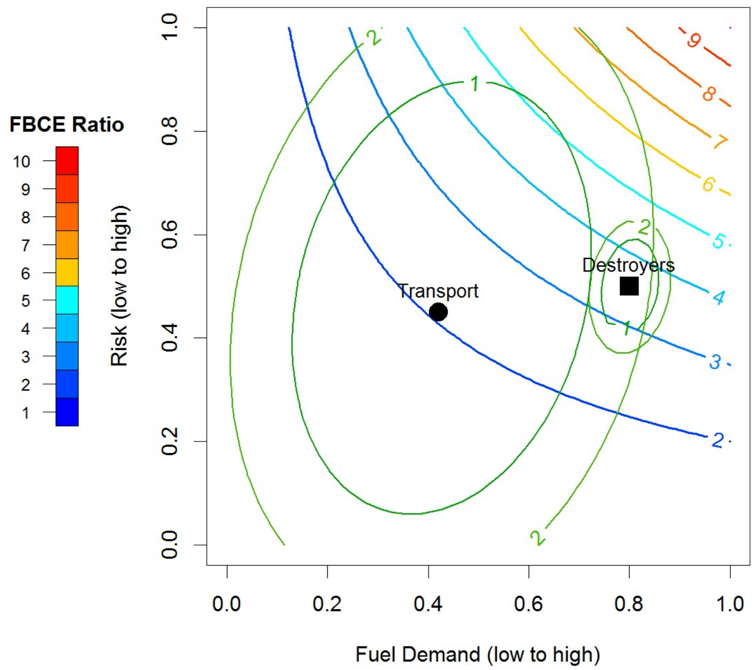

Figure 5.9: FBCE Ratio Solution Space Per Soldier Long-Term

Figure 5.10 shows the CDFs for this mapping. While possibly avoidable in the previous example, creating a metric that appreciates energy at this level in future decisions compels a thorough understanding of personal and organization risk preferences. As shown, the transport option has a markedly lower expected FBCE Ratio at the expense of a potentially ruinous tail.

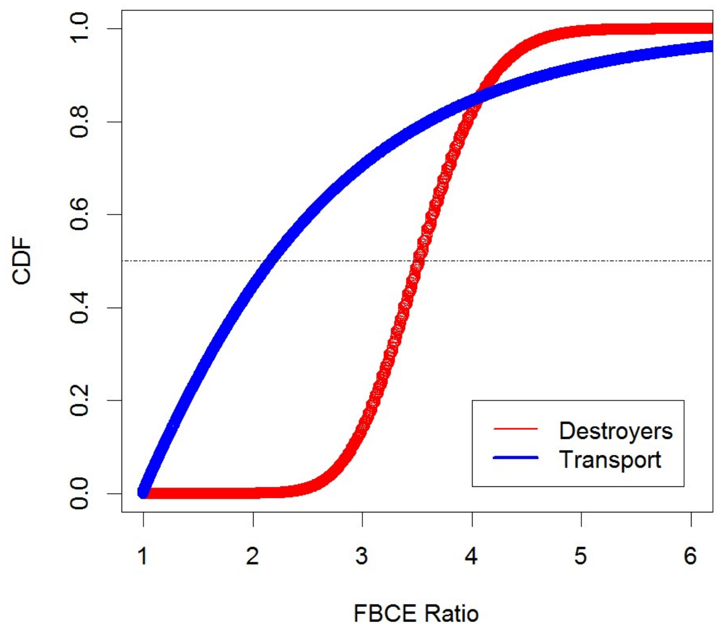

Figure 5.10: FBCE Ratio CDF Per Soldier Long-Term

As mentioned throughout this example, the relevance of this metric is dependent on details of the analysis and the preferences of the decision maker. Accordingly, a priori of that, this work cannot claim this framework conclusively results in more relevance to the decision maker. However, this level of information is certainly more than most other FBCE methods or the analysis in previous sections could provide. Accordingly, this method is better suited to meet the changing and complex needs of an acquisition or operational decision maker, where there is a higher chance of relevance across a wide range possible decisions and decision makers [5].

5.4 Conclusions

This chapter provided additional justification for the importance of uncertainty in FBCE decisions and provided an example of the proposed framework that incorporated capability. As shown, the proposed framework arms decision makers with a rapidly deployable, flexible method unrestricted by the data and assumptions of past military operations, unlike previous

FBCE attempts. Additionally, this framework meaningfully represents the uncertainty inherent in forecasting, which creates the opportunity to incorporate several dimensions of energy such factors as cost, risk, and resilience into decision making [6]. Such an approach may quickly become critically important as several force changing technologies loom on the horizon and threaten organization-wide reshaping, such as unmanned systems. Acquisition decisions will need to account for these changes as well as potentially significant differences between the future systems themselves.

As mentioned, this framework also attempted to, at least notionally, address two critical considerations usually assumed away in other analysis: system capability and the interconnection between combatants' energy space. FBCE, or any such similar burdened logistic metric, are a part of the measure of a system's efficiency and sustainability, which themselves do not entirely encapsulate a system's capabilities or operational value to the military [7]. Ultimately, the DoD exists to successfully carry out the objectives deemed important by the U.S. government. While prioritizing the mission, military commanders also highly value the lives entrusted to their care. Within this mindset, historic acquisition decisions have perceived increased logistic demand as a necessary consequence of, or secondary consideration to, increased combat capability. To truly understand the value of FBCE, it may be necessary to attempt to quantify it within the rest of a system's capability space and account for that which is interconnected with the opponent's capability and energy space [8]. Briefly discussed, personal energy costs and risks are liabilities that need to be properly managed in decision processes. Likewise, opponent's energy costs and risks are opportunities that need to be properly exploited in decision processes. Accordingly, there is value in a system's ability to mitigate its own or created energy demands and risk as well as an ability to exploit those same attributes for an uncertain opponent's systems. Properly valuing burdened energy costs requiring appreciation of this duel nature in decision processes.

For the example used through this work, sometimes a shadow of capability was incorporated. As shown, even this simplification of capability and its connection to the opponent's energy space significantly impacted the decision space; further demonstrating the need to find a way to involve capability and game theory analysis without so many generalizing assumptions. This would allow for a detailed discussion of the value of reducing personal system's potential logistic cost and risk that improves mission capability and saves lives within the greater system tradeoff analysis and/or creating the opportunity to exacerbate those same features in the opponents of future conflicts.

5.5 References

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Chapter 6: Including Deep Uncertainty and Capability into Burdened Energy Calculations

Abstract

In previous papers, we proposed and demonstrated the use of a new framework to better incorporate energy costs and uncertainty in military decisions. In this paper, we expand on the complex conversation of energy in military tradespace and offer further adjustments to that framework. These adjustments are specifically designed to deal with the issues of scoping a deeply uncertainly problem and creating a tradespace to directly compare system capabilities and FBCE. We then demonstrate its use and value to the decision-maker with nominal present-day systems and possible future technologies.

6.1 Motivation

The United States DoD consumes a tremendous amount of petroleum products on operations powering its portfolio of air, sea, and ground vehicles, as well as providing energy services to stationary and mobile groups of personnel. This dependence on petroleum-based fuels and sensitivity to market price uncertainty create a significant risk to the organization, which at the very least can lead to short-term disruptions [1].

The commodity cost of energy is arguably the least important component of the total cost of energy for many decision makers in the DoD. Energy has several first-order impacts on the operational capabilities of any system. Tactical systems that demand more energy create larger or more frequent resupply requirements that increase the probability and consequence of interdiction and energy disruption. Some historic examples showing capability consequences and other costs of using metrics that fail to incorporate energy in all its dimensions into decision processes or do so poorly were highlighted in Chapters 2 and 3.

Qualitatively, these risks are understood. Originally known as Fully Burdened Cost of Fuel, the DoD created a metric in 2007 now known as Fully Burdened Cost of Energy (FBCE) to better value these hidden costs during the acquisition process.

Originally, FBCE was embraced by all DoD Service Branches. Anecdotally, while its importance seems to be better understood and more accepted, support for FBCE has waned significantly since 2012. A detailed examination of the development of this concept in the DoD and DoN can be found in Chapter 4

Accordingly, there remains a need for a DoD-wide method that properly highlights the true cost and risks of energy reliance in acquisition decisions across a range of future possibilities. In previous papers, we proposed and demonstrated the use of a new framework to incorporate energy costs and uncertainty in military decisions better. Our aim is to create a metric simple enough to be quickly incorporated into decision-making processes and supply zeroth order estimates to gauge value of further refinement, flexible enough to adapt to the fluid demands and constraints of operations and planning as well as possible organization changing technologies, and complex enough to include all the critical dimensions of energy.

To accomplish this aim, the first section of this work expands on the complex conversation of energy in military tradespace, beginning with a focus on monetary concerns and then enlarging the focus to other concerns (e.g., technological change and uncertain security environment). We then demonstrate some of the energy, capability, and logistic implications of this discussion with a comparison between conventional and directed-energy weapons. We next discuss adjustments to a framework introduced in Chapter 2. These adjustments are specifically designed to create a tradespace to compare system capabilities and FBCE across a deeply uncertain security and technology environment directly. We demonstrate the potential value of these changes to decision makers with several examples that draw data from publically available sources to include both present-day and potential future weapon systems (e.g., directed-energy weapons and autonomous, unmanned systems). Using publically available sources keeps the framework open to academic discussion and improvement. Later, decision makers can populate this framework with classified, real-world data. The paper ends with conclusions, policy implications, and recommendations for future work

6.2 The Monetary Cost of Energy Dependence

Because oil is a global commodity, total DoD spending on petroleum products is highly sensitive to volatile market prices and a multitude of other factors outside of its control. In previous works, we examined the quantity of military energy demand, those monetary costs over time, their correlation to external security events, and scalability concerns. This section expands that conversation.

The DoD's large expenditures on energy are significantly dependent on forces outside its control and represent a risk to organizational capabilities. There are also several critical correlations, some of which are poorly understood, between the oil market and DoD operations. Lee and Cheng found that both the first Gulf War and the 2003 invasion of Iraq led to large jumps in spot oil prices [2]. Other research found that even the threat of military conflict seems to appreciably impact oil prices even during a period with excess oil stocks, weak demand, and overcapacity [3]. Another report found a statistically significant relationship between US military action and oil prices, with annual oil prices increasing 25-55% when the US engages in large scale, longer-term military conflict and daily oil prices increasing 8-12% during shorter-term conflict in oil-sensitive regions [4]. This report analyzed the conflicts from 1972-2007, a section of history without certain types of engagements (e.g., near-peer, multi-national or global wars). The magnitude of the impacts to oil markets from such potential future conflicts remains uncertain but is likely to be very large.

Other cost drivers are completely outside the influence of the DoD. A 2009 report found that some refining cost increases were due to refiners handling heavier sour crude oils and new US EPA regulations to reduce sulfur in highway-use diesel fuels [5]. Some additional cost drivers include many general trends such as growing world demand, limited or fluctuating refining capacity, and short-term fluctuations caused by specific events (e.g., Hurricane Katrina) [6]–[8]. While the military has little ability to impact these factors, these drivers may be correlated to the probability of military action. For example, growing world demand relative to a fixed supply may be related to probability of conflicts, which is correlated to the chance of military intervention. Accordingly, a large-scale natural disaster event may impact market prices at the same time that it increases the need for military assistance, which itself may impact market prices.

The established safeguards may be less helpful than thought and have common failure modes. The Defense Logistics Agency-Energy (DLA-E) acts as a buffer to small fluctuations but any difference must ultimately be covered by the Defense Working Capital Fund [9], [10]. As DLA-E does not hedge contracts or attempt to store enough fuel to cover periods of market price increases, resulting budget shortfalls to cover market-tied fuel pricing has traditionally been met by Congressional requests for supplementary funds [4]. Historically, this has led to short-term operational disruptions and use of emergency appropriations, which has its own hidden costs [1].

DLA-E and DoD price control and forecasting methods have not yet evolved to handle the variability of recent petroleum markets and these uncontrollable forces. Between 2000 and 2011, Department of Defense (DOD) annual fuel expenditures were between $1 and $9 billion higher than budget estimates, excluding the underestimate in 2009, when fuel expenditures accounted for between 1.4% and 3.2% of their budget. Analysis shows cost variance was responsible for 80% of the fuel-budget variance on average, while consumption variance accounted for the rest. Consumption variance was particularly important during the beginning of the wars in Afghanistan and Iraq. In the last few years of the Afghanistan conflict, the military services experienced end-of-year funding shortfalls for fuel, necessitating requests to Congress for supplemental funding, shifting of funds to "must-pay" fuel bills, and reducing operations [1], [11], [12]. In the end, a widely varying fuel budget and persistent use of emergency appropriations prevented Congress and potentially even the DoD from fully understanding even the financial costs of energy in military operations during this time frame [13].

Even the Strategic Petroleum Reserve (SPR) has a more limited ability to relieve military demand during a crisis than some might think [14]. In 2006, 40% of the refined product in the US was heavier than that stored in the SPR [15]. Additionally, almost half of US refineries are tooled to refine heavier oil than what is traditionally stored in the reserve. In the event of a significant military demand, it would take time and money to adjust refineries to handle the oil in the reserve [15].

6.3 Energy: A Complicated Resource

Designing a framework that properly translates the costs and benefits of energy to military decision makers requires appreciation beyond finances. There are complex, uncertain, and dynamic relationships between energy, logistics, and military capabilities that make its value simultaneously difficult and critical to encapsulate in a metric.

DoD spends a lot of money to satisfy a large demand for petroleum but that consumption is not only created by combat forces. Fuel must be moved from points of sale to end-users, which can require complex, military-owned logistic webs (e.g., ships, vehicles, aircraft, people, generators, computers) that consume fuel themselves. It is estimated that around half of all DoD personnel and a third of the total budget are dedicated to logistics [16]. For the Department of

Navy (DON), reports estimate 90% of naval logistics and 70% of expeditionary logistics are fuel and water [17], [18]. Others estimate fuel to be 70% of total ground logistics by tonnage and about 50% of average convoy load by volume [19], [20].

The portion of total fuel consumed by logistics and the portion of total costs and risk created by logistics are dependent on many factors that are not well understood. Today, the logistic networks necessary and the costs and risk to acquire, staff, maintain and operate these networks are dependent on a wide array of factors. The DoD can control some and influence others (e.g., which weapon and logistic systems to buy and where to base them). However, it is critical to recognize that, like oil markets, some important factors are outside the organization's control (e.g., opponent impact on logistic and end-user loss rates and logistic escort requirements). Even some factors, like time and location of operations and their impact on influential factors (e.g., weather, terrain, and logistic chain length), are only controllable within a field of limited options determined by forces outside the DoD. For example, the military can choose to put combat forces in Bagram, Afghanistan and how to meet the energy needs of those forces but the need to be in that region was made by Presidential action in response to unprecedented actions by a terrorist group. These factors and relationships are not well understood or encapsulated in reported fuel cost figures. As a result, even the portion of present-day fuel consumption created by logistics is very difficult to determine. More importantly, the resulting logistic costs and risk represent additional, ambiguous, potentially very large expenses that the organization must absorb but can only partially plan for [21]–[23].

Adding to the challenge, these factors and their relationships to military capabilities, energy, and logistics may fundamentally change because of force evolving technologies, such as directed-energy weapons and autonomous, unmanned systems. While it has a history of performance shortfalls, the DoD has pursued the development of directed-energy weapons since the 1960's [24]. While the DoD has yet to field a directed-energy weapon system operationally, recent developments are promising. In 2012, the Air Force demonstrated the feasibility of airborne high-power microwave weapons [25]. Over the next two years, the Navy demonstrated the ability of ship-based lasers to shoot down drones and detonate exposed ordnance on enemy ships [26], [27]. Whether, when, and in what form these systems become operational is an issue of some contention and recent signals are mixed [24], [28]–[30]. However, if implemented, directed-energy weapons could have far reaching impacts on military capabilities, energy demands, logistics, and the relationships between them.[16] In the future, certain planning processes (e.g., Munitions Requirements Process) may be greatly simplified by the versatility of directed-energy weapons. They may also simplify future logistics, where assortments of various munitions and ordnance may be replaced with the common currency of energy. However, there is also the possibility that these benefits may be outweighed by the additional logistic demands of new components needed to maintain these systems. The impact to the size of future logistics is similarly uncertainty. If operationally fielded, these future weapon systems would free some portion of present-day logistics that deliver ordnance, which in recent operations has been fairly small. Depending on where directed-energy weapons are placed within the battlespace, their efficiency, and how their energy demand is satisfied, the overall impact to the size of logistics required per combat system may increase, decrease, or remain relatively similar to present-day.

[16] Though not technically directed-energy weapons, other potential future weapon systems (e.g., electromagnetic railguns) may have similar impacts [99], [100].

There are not many technology umbrellas as expansive or thoroughly discussed as unmanned systems [31]–[41]. Over the years, these systems have contributed significantly to missions generally described as “dull, dirty, or dangerous” across a diverse set of Joint Capability Areas (JCAs) (e.g., Battlespace Awareness, Force Application, Protection and Logistics). Unlike other technologies (e.g., directed-energy weapons), even the downward financial pressures of recent years has not significantly impacted the military’s vision for these systems and for some, it has reinforced their importance as cost-effective, risk-reducing, and, eventually through autonomy, potentially less personnel-intensive alternatives [42]–[57]. While there remain a lot of policy and implementation challenges (e.g., interoperability, autonomy, and integration), these systems could have far-reaching implications for future military capabilities, energy, logistics and the relationships between them. For example, present or next generation unmanned systems may significantly reduce the demand for energy and the cost to resupply it. Light-weight, low-power unmanned systems might replace manned systems for particular mission sets. This could reduce energy demand through sheer efficiency or through some combination with renewable offsets, where lower power demands over time can be partially met with onboard solar panels, or by leeching off native power infrastructure. Besides smaller demands reducing energy costs, unmanned systems integrated into logistic chains could further reduce expenses by removing human assets from risk. In addition to first-order impacts, this could affect a decision maker’s choice to allocate escorts to resupply, which can significantly alter both military capabilities and logistic cost further. In the near future, the consequences of these impacts are uncertain. The loss rates of logistic resupply might increase without escorts. They also might remain relatively unchanged or even decrease as escort assets, without the need to protect logistic lines, can continue their combat missions, draw opponent focus, and reduce logistic vulnerability. Even if logistic loss rates increase, costs may not once risk to human life and high-value escort assets are removed. Even if it does increase, military decision makers may not focus on monetary cost in some operations if the throughput of unmanned, replaceable resupply is meeting operational demand. A little further into this technology's development, logistic networks may look remarkably different than their contemporary counterparts. Networks of autonomous, relatively disposable systems in the air, on or under the sea, and on the ground may work together sharing updated information on risk (e.g., opponent action and other ground-, air- and sea-based threats) while independently avoiding or addressing these threats as they coordinate individual rendezvouses with their manned and unmanned combat systems. Aided by other unmanned systems gathering information on allied and opponent actions, diffusing roadside bombs, and removing sea-based mines, these logistic systems of the future may fundamentally reduce the value of and need for some other logistic mainstays such as convoys and depots.

In addition to the uncertainty created by technological change and force development, recent international history and military action has been one marked by surprise. Traditional, Cold War-era defense resource planning employed a lot of predict-then-act approaches, where experts took available data to predict "most likely" futures and then suggest optimal strategies to operate in those futures. These methods worked reasonably well when international politics and events were dominated by a handful of relatively predictable players, especially state actors. Today, the DoD has to operate in a security environment marked by uncertainty and surprise. In this environment, attempting to use predict-then-act approaches or other modeling heavily reliant on future predictions is likely to lead to either failure in preparation or, even before that, gridlock if experts disagree on the most likely futures [58].

This brief discussion simultaneously highlights the importance and challenge of incorporating energy into future decisions and tradespace analysis. In summary, we illustrated how any energy decision metric needs to incorporate the fuel consumption of the systems and people delivering it, the consequences of energy shortfall/value of efficiency and resilience, the relationships between military capabilities, energy, and logistics, the wide array of factors that influence those relationships, some of which are outside the control of the DoD, and the wide range of potential futures while still allowing for some likelihood of predictive failure[59]. Some of this uncertain future is due to the possibility of looming force changing technologies and some from the large uncertainty of international events. Otherwise, in addition to uncertain and sometimes large energy costs, there is a real risk that logistic challenges will severely impede the capabilities of future U.S. forces.

6.4 Directed-Energy Weapon Example

As highlighted previously, directed-energy weapons can have significant impacts on military capabilities, energy demand, logistics and their relationships. Decisions on whether and how to field these systems requires perception of many costs and benefits, some of which require novel thinking of those concepts. This section contains such a comparison between the AGM-114 Hellfire and the Advanced Tactical Laser (ATL). This comparison introduces the interplay between capabilities, energy demand, and logistics and encourages the general discussion’s development.

First, some background on the two weapon systems. The Hellfire can be launched from a variety of rotary, fixed-wing, and unmanned air systems. While originally designed as an air-to-surface anti-tank missile, the Hellfire has been used against an assortment of targets ranging from unarmored to heavily armored. The missile has a length of 1.63m, a diameter of 17.8cm, weight of about 45kg, range of 8,000m, and a unit cost between $65,000 and $110,000 domestically and upwards of $160,000 overseas [60]–[62].

The ATL is a 100 kW-class chemical oxygen iodine laser mounted in a C-130. The system weighs around 6,000kg and has a range of around 20,000m. While at this time its development has been discontinued, the program did achieve some successes, including demonstrated effectiveness against lightly armored targets [63]–[65]. Future operational directed-energy weapon systems can build off these achievements and may have similar characteristics [30]. Additionally, because of the data gathered on the ATL, there is potential for future directed-energy weapon systems with similar performance to have capability overlap with the Hellfire. While this overlap is unlikely to be all inclusive (i.e., some heavily armored targets will most likely remain outside the capabilities of near-future lasers), weapons like the ATL could be used in place of the Hellfire for some section of current missions.

The comparison of any dramatically different weapon systems requires a common reference unit of capability. For this comparison, total energy or some such measure of destructive capability is not viable. Over their centuries of development, conventional weapons have evolved into very compact delivery systems of kinetic, thermal, and chemical energy so much so that especially early iterations of directed-energy weapons cannot begin to compare.[17] However, the goal, especially in modern militaries, is to use a weapon less to impart potentially ineffectual destruction and more to focus the necessary energy to cause a specific effect on a particular target. Directed-energy weapons simply attempt to do this with the concentrated application of non-kinetic energy. The challenge is then to find a way to relate the various properties of different weapons to the concept of effectiveness. One such way to confront this challenge is through the Joint Munitions Effectiveness Manuals (JMEM), which are used to determine the effectiveness of air-delivered weapons against a variety of ground targets [66]. While there are limitations to these equations, they create a starting point.

For conventional weapons, the single sortie probability of damage ($SSPD$) is calculated as:

$$SSPD = \frac{L'_{ET} + W'_{ET}}{\sqrt{\left(17.6 * REP'^2 + {L'_{ET}}^2\right) * \left(17.6 * DEP'^2 + {W'_{ET}}^2\right)}} \quad \textbf{6.1}$$

where effective target length (L'_{ET}), effective target width (W'_{ET}), equivalent range error probable (REP'), and equivalent deflective error probable (DEP') are defined as:

$$L'_{ET} = 2 * WR_r \quad \textbf{6.2}$$

$$W'_{ET} = 2 * WR_d \quad \textbf{6.3}$$

$$REP' = \sqrt{REP^2 + x_{br}^2} \quad \textbf{6.4}$$

---

[17] Though such a comparison might be possible between conventional and directed-energy like weapons (e.g., railguns). Meaningful cost and logistic savings might be found through the investment of such future weapon systems on nuclear-powered ships.

$$DEP' = \sqrt{DEP^2 + x_{bd}^2} \quad \textbf{6.5}$$

Weapon radius in range (WR_r), weapon radius in deflection (WR_d), ballistic dispersion error in range (x_{br}), ballistic dispersion error in deflection (x_{bd}), and aspect ratio (a) are defined as:

$$WR_r = \sqrt{MAE_f * \frac{a}{\pi}} \quad \textbf{6.6}$$

$$WR_d = \frac{WR_r}{a} \quad \textbf{6.7}$$

$$x_{br} = \frac{0.6745 * SR * \sigma_b}{1000 * sin(I)} \quad \textbf{6.8}$$

$$x_{bd} = \frac{0.6745 * SR * \sigma_b}{1000} \quad \textbf{6.9}$$

$$a = max[1 - 0.8 * cos(I), 0.3] \quad \textbf{6.10}$$

Finally, range error probable (REP), deflective error probable (DEP), mean area of effectiveness due to fragments (MAE_f), slant range (SR), milliradians of ballistic dispersion in the normal plane (σ_b), and impact angle (I) are functions of the weapon system. Using an REP and DEP of 5m, SR of 4,000m, I of 90°, σ_b of 1 mrad, and MAE_f of $100m^2$, the hellfire has a SSPD of 0.41.

After accounting for the differences, the equivalent of SSPD for directed-energy weapons is Laser Single Sortie Probability of Effect ($LSSPE$), which is defined below [67]:

$$LSSPE = \frac{Fluency + SS^2}{ERM + SS^2} \quad \textbf{6.11}$$

Fluency is the product of irradiance, a function of slant range and the laser, and laze time, determined by the user. Spot size (*SS*) is the focal area of the laser and also determined by the user. For any laser, a spot size must be chosen that is large enough to capture the majority of the beam but not so large as to overly distribute the energy. Based on testing, a good spot size for the ATL is $36cm^2$.[63] Energy Required to Melt (*ERM*) is as named and determined by the target. Some sample ERMs released by AFRL/DE are shown in Table 6.1 and extend from unarmored to lightly armored vehicles:

Table 6.1: Energy Required to Melt Data [63]

Material	Thickness	ERM (J/cm^2)
Prime and Painted Steel	0.080"	2,500
	2 Layers, 0.080" (2nd bare)	5,000
	0.160"	5,000
	2 Layers, 0.160" (2nd bare)	9,900

Ignoring atmospheric effects, Figure 6.1 shows the LSSPE for the ATL with an SS of $36cm^2$ and an ERM of 10,000 J/cm^2.

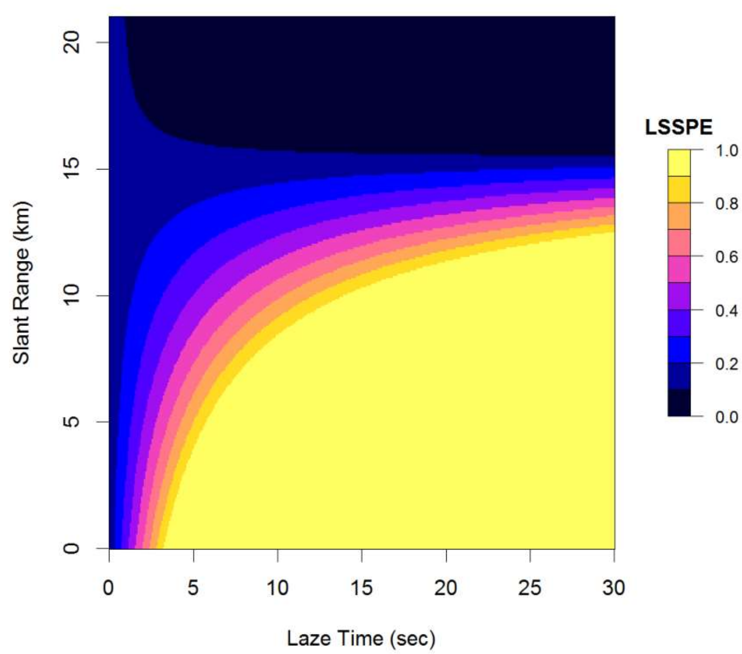

Figure 6.1: LSSPE for 2 Layers 0.160" Steel (ERM of 10,000 J/cm^2)

Based on this, the ATL requires a laze time of around 2 seconds to achieve a LSSPE of 100% against a target with an ERM of 2,500 J/cm^2 and around 6 seconds against a target with an ERM of 10,000 J/cm^2.[18] To be conservative, the rest of this analysis assumed a 10-sec laze time.

Before estimating fuel consumption, there is an important note to make here. Because of the difference between the Hellfire's SSPD and the ATL's LSSPE, a one-to-one comparison may not be appropriate for the range of targets defined by the assumptions of this analysis. The consequences of these performance differences are made revalent by using a geometric distribution, which is the probability distribution of the number of Bernoulli trials needed to obtain one success.

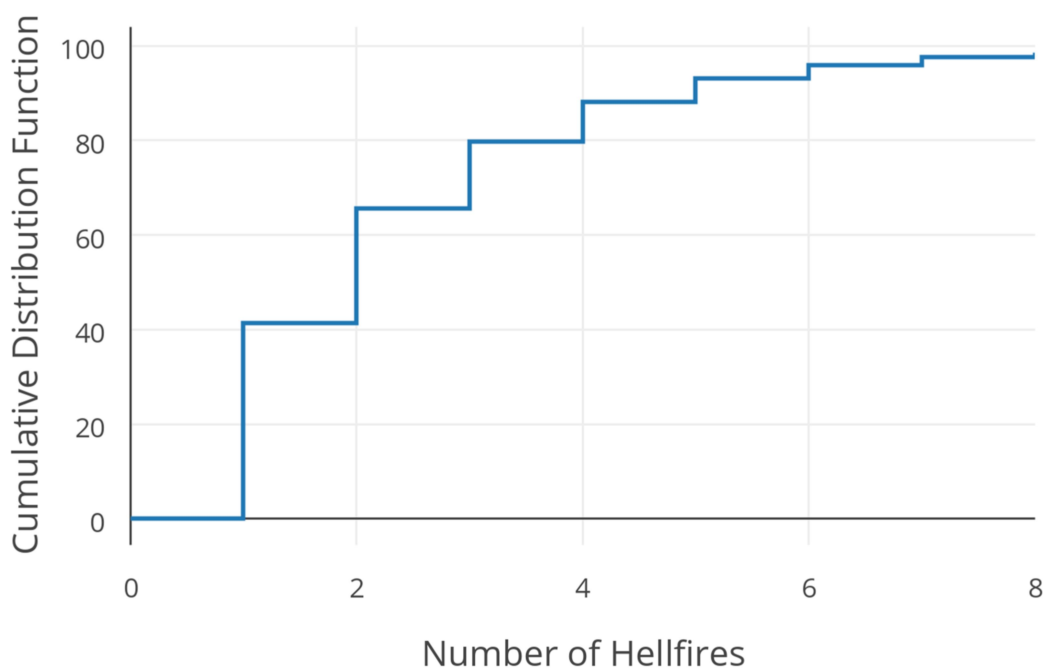

Figure 6.2: Probability of At Least 1 Success

[18] The capabilities of the ATL are not necessarily limited to this range of ERMs and extrapolation could extend analysis. However, we have held analysis to this range as it serves our purpose of showing capability overlap and the differing impacts to energy demand and logistics.

As the cumulative distribution function illustrates in Figure 6.2, there is no number of Hellfires that guarantees the same performance though additional Hellfires increases the probability of at least one success (e.g., two has a 66% of at least one success and three an 80%). For the remainder of this analysis, one Hellfire is compared to one laser effect, a 10-second "shot." However, it is important to keep in mind that, depending on the decision maker or application, the costs of the Hellfire and relative benefits of the ATL should arguably be multiplied by some factor.

Assuming the energy for the laser is not supplied from the native aircraft systems, the power needs to be created by some onboard system. The military has a large inventory of diesel generators in addition to spare parts and maintainers. Figure 6.3 shows the fuel consumption rates for diesel generators with the specified capacity across the power range demanded by the ATL. However, in case issues (e.g., thinner air while flying or exhaust) prevent the use of an unmodified diesel generator, this analysis also includes auxiliary power units (APUs).

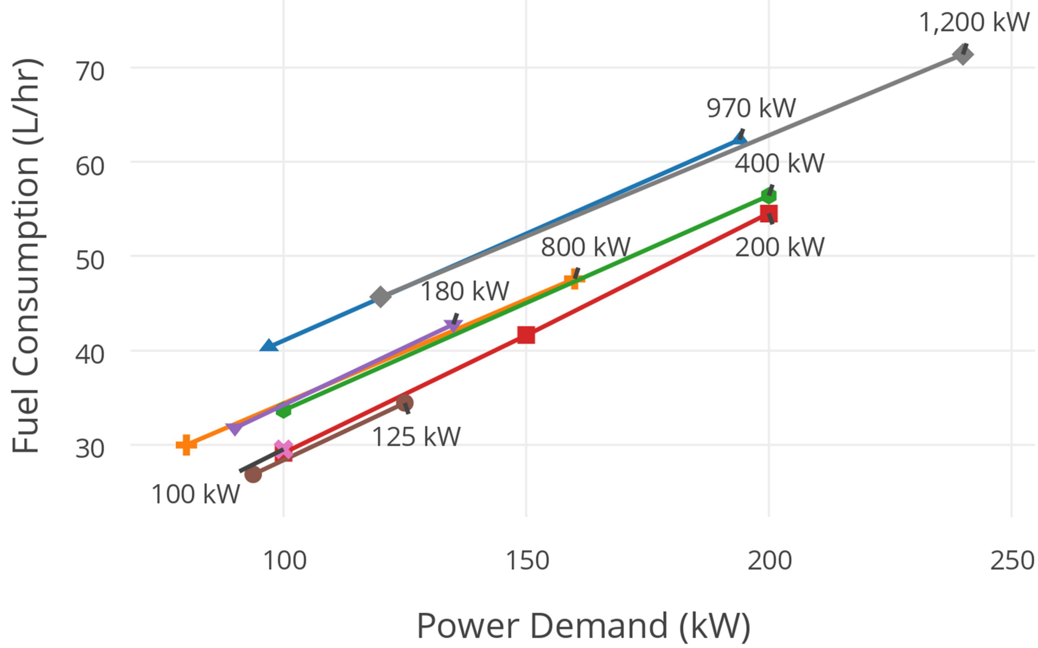

Figure 6.3: Efficiency of Various Diesel Generators [68]–[71]

APUs are common components on aircraft that provide electric, pneumatic, and/or hydraulic power for various operations (e.g., starting engines and in-flight backup). For this analysis, APUs are an alternative means to power the laser; one that is already designed to operate in flight conditions. However, using APUs for this analysis brings its own challenges. Besides size, the fuel consumption of an APU depends on the combined workload and atmospheric conditions (e.g., temperature and density altitude). However, data across a range of electrical and other workloads and atmospheric conditions was not available. For a conservative estimate, Table 6.2 shows the highest fuel consumption found for the APUs of aircraft of similar and larger size than the C-130.

Table 6.2: Ground APU Fuel Consumption [72]–[74]

Aircraft	Fuel Consumption (L/hr)
B727	125
B757	143
B767	143
DC-10	173
A320	176
A321	176
B777	365
B747-400	433
B747	460

Based on this data, a conservative estimate for the fuel consumption of an additional APU is around 230 liters per hour with an upper range estimate around 460.

Next, to estimate the fuel demand, we assume the power source has to run for five minutes per laser shot. With a better understanding of the power source's peak supportable load, fuel consumption during idle periods, and the requirements and limitations of capacitors and other conditioning equipment, this may be a very conservative estimate of the fuel requirements. Table 6.3 shows the fuel estimates carried forward in the analysis and the lower end of where the actual requirement would be if the power source could support the instantaneous demands of a 10-second laze time and spend the remainder of the running time at idle.

Table 6.3: Fuel Consumption (liters per)

Power Source	Generator Low	Generator High	APU Conservative	APU High
Hour	28	41	230	460
Laser Effect	2.3	3.4	19	38
Laser Effect w/idle	0.38	1.4	9.8	20

Using the laser effect fuel consumption estimates, Table 6.4 compares the Hellfire and ATL with various power sources across several metrics. The calculations do not include the added bulk or weight of any shipping material (e.g., boxes for the missiles or containers for the fuel). As shown, all power sources achieve significant reductions in the volume and weight required to be transported per effect. Even modest reductions in these measures can have cascading impacts on logistics. Across a common window of time and logistic systems, decreasing volume allows for more capability or fewer or less frequent resupply convoys. Depending on the operation, frequency and size of convoys can have impacts on many factors such as loss rates and escort demands. Weight savings also have indirect benefits such as improving the fuel efficiency of logistic vehicles and widening the range of infrastructure where they can operate. Additionally, the ATL simplifies logistics, requiring a resource already part of a greater demand. Lastly, with fuel available at $2 per gallon[19], monetary costs are almost eliminated. Some of this is due to the boundaries of the analysis and a more thorough cost analysis follows after some important cost components are included.

Table 6.4: Comparison Per Capability/Effect

	Volume (L)	Reduction	Density (kg/L)	Weight (kg)	Reduction	Cost	Reduction
Hellfire	40.6	-	1.11	45	-	$65,000	-
Fuel for Generator-Low	2.33	94%	0.832	1.94	96%	$1.23	100.00%
Fuel for Generator-High	3.42	92%	0.832	2.84	94%	$1.81	100.00%
Fuel for APU-Conservative	18.9	53%	0.8	15.1	66%	$9.99	99.98%
Fuel for APU-High	37.9	7%	0.8	30.3	33%	$20.00	99.97%

Even when taken in context, these potential savings could have organizational-level impacts. The percent of logistics used to resupply munitions for the latest conflicts was around 10% of which Hellfires represents just a portion [20]. Still with a dramatic reduction in munitions logistic demand by volume, a more dramatic reduction by weight, and the snowballing

[19] The most recent release from DLA-E prices diesel and jet fuel products between $1.62 and $1.95 per gallon.

benefits throughout, even replacing some Hellfire targets with the fuel required by the ATL to generate similar capability could have significant impacts to total logistic demands.

To make the costs more comparable, the boundaries of the analysis need to be expanded to at least include the delivery system. Specifically, we want to compare the cost per day to use the ATL and Hellfire for an uncertain number of targets, where the costs include the fuel consumed by the delivery system. We assume a C-130H for the ATL and a MQ-1 Predator for the hellfire, which was thought to be the most fuel efficient, lowest cost per flight hour option. The C-130H consumes between 4,000 and 10,000 pounds per hour depending on such factors as weight and phase of flight [75]–[78]. For this analysis, we used 7,000 pounds to conservatively reflect the moderate weight of the ATL (e.g., about one-third of the max payload of the aircraft) and a vast majority of the flight profile spent at loiter (e.g., maximum endurance). The estimated fuel consumption for the Predator is 100 pounds per hour [46]. For the mission profiles below, each system combination has a fixed and variable cost. The fixed cost is the expense of the total fuel burned by the delivery system over an 8-hour day and the variable cost is the expense of using the respective weapon. Because the costs of the power sources are so close, only the highest estimate (i.e., APU High) is shown. In addition to graphing the cost in terms of commodity price, Figure 6.4 also shows profiles using the median FBCE calculated through our framework with error bars showing the 5th to 95th range and total cost per flight hour (PFH). The FBCE assumes the same future to aid comparison, minus those differences created by the dissimilarities in the quantity of energy demanded. The same logistic infrastructure is used to move the energy required the same 600 miles each-way in the same low-risk environment without escorts to the same base. This incorporates some new costs such as the fuel necessary to carry the fuel. Both systems face uncertainty in their fuel requirements, though the quantity of uncertainty and related expenses are much higher for the C-130H. Methodologies for generating PFH costs vary but in general attempt to include all the major operations and support expenses [79], [80]. The highest found is graphed in the figure after adjusting for inflation.

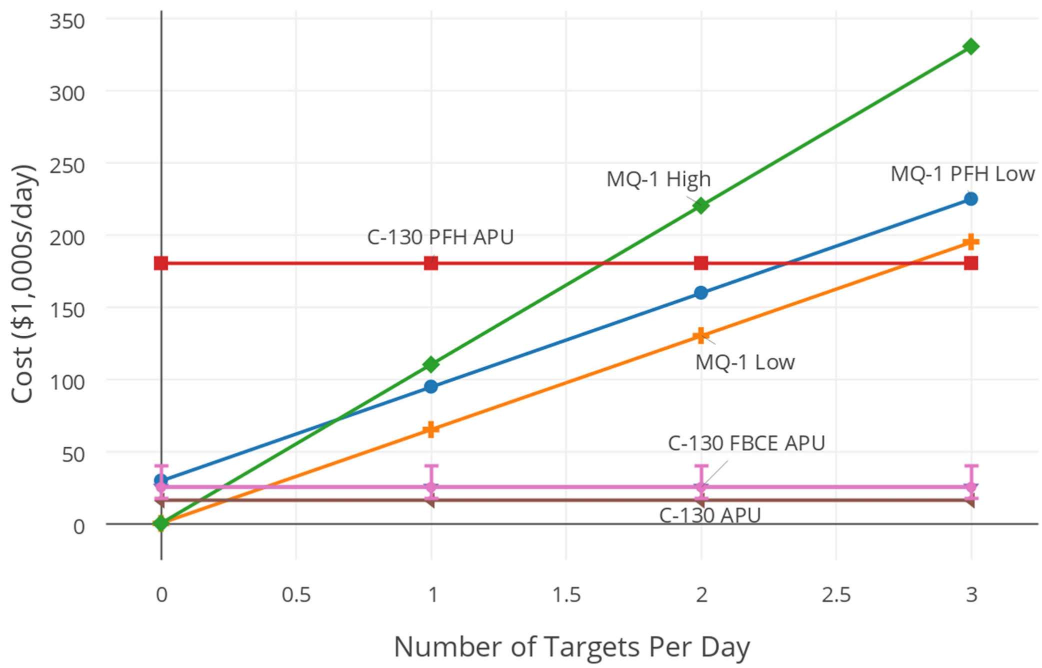

Figure 6.4: Cost Effectiveness as a function of Targets Per Day

The figure reveals three trends. First, the breakeven point for all comparisons occurs before three targets per day with some crossing before two. Second, because of the low energy demands of the ATL and the Predator, the cost comparison is almost entirely dominated by the C-130H's fuel consumption and the cost of the missile. Third, as setup, burdening the energy and incorporating FBCE does not significantly impact the intersection point.[20] This demonstrates the proposed framework's value by enabling decision makers to quickly determine an estimate for burdened energy costs, assess its relative significance for this analysis, and logically prioritize

[20] The FBCE distribution for the MQ-1 was originally included as part of the analysis but is not noticeably different at this scale.

further limited resources. Confidence in this conclusion could be increased by exploring FBCE's sensitivity across a wider set of envisioned futures and corresponding assumptions.

The final part of this analysis seeks to highlight how the differences in logistic demands of the ATL and Hellfire impact capability. Both parts assume the use of Class 8 freight trucks with 48' wedge trailers. While not a quintessential military supply vehicle, these trucks serve a vital role in most logistic networks, especially in the United States and probably play some role in most military supply chains though most likely removed from battle zones. First, the number of Hellfires necessary to fill such a trailer is calculated. Around 500 Hellfires reach the mass limits of the vehicle. Then trailers are filled with the amount of fuel necessary to generate the same number of effects. Table 6.5 shows the estimated range and fuel consumption for a 600-mile, one-way trip using a fuel efficiency regression fit to vehicle weight [81]. Interesting the dramatic weight reductions have a dampened impact on these measures of efficiency. This is mostly due to the tradeoff between fuel efficiency (i.e., miles per gallon) and cargo efficiency (ton-miles/gallon). As weight increases, fuel efficiency decreases slower than cargo efficiency increases.

Table 6.5: Class 8 Freight Truck Efficiency with 500 Hellfires or Equivalent Effects

	Hellfire	Gen Low	Gen High	APU Ave	APU High
Payload (lb)	50,000	2,160	3,160	16,800	33,700
% Decrease	-	96%	94%	66%	33%
Range (miles)	1,830	2,360	2,360	2,260	2,070
% Increase	-	29%	29%	23%	13%
Fuel for 600 mile one-way (gal)	83	64	64	67	73
% Decrease	-	23%	23%	19%	12%

While an interesting note, these results have limited application as, for the reason listed above and others, organizations usually doesn't send mostly empty resupply vehicles.

Accordingly, this second part examines the capability differences created by the payload limitations of this supply vehicle. The results illustrated in Table 6.6 highlight an easy to miss but potentially important consideration that for this analysis favors the ATL. Because of the lower density of the fuel and the relationship between volume and mass limitations for this particular vehicle, there is a boost in the ATL's capability advantage.

Table 6.6: For Max Filled Class 8 Freight Truck of Respective Weapon/Power Source Energy

	Hellfire	Gen Low	Gen High	APU Ave	APU High
# Shots @ Max Payload	500	11,700	8,000	1,500	750
% Increase	-	2,200%	1,500%	200%	48%
% of Max Volume	20%	27%	27%	28%	28%

Besides those analyzed, there are a host of other costs and benefits that could be incorporated into this comparison. Diesel and jet fuel are both combustible. Depending on an opponent's capabilities, this may increase the risk per resupply though this increase in risk is most likely dominated at the organizational level by the ATL's significant reduction in the number and/or frequency of convoys. Hellfires, on the other hand, are relatively inert before arming though there would be more convoys in transit for the same capability. While inherently more vulnerable to attack, fuel convoys create less concern if seized by an opponent, the probability of which is lower because of the ATL's logistic differences. While no military wants to aid his opponent, the loss of fuel is much less consequential compared to the loss of modern, versatile munitions like Hellfires. Some of the previous analysis assumed a 600 mile one-way ground-based delivery network to highlight the importance of end-user energy demand. The purpose was to demonstrate the non-linear consequences of pulling additional energy through the same logistic network. As in that analysis, fuel and munitions may have logistic networks with many common components depending on the operation and especially as they approach a common destination. However, widening the purview to include fuel and Hellfire producers reveals fundamentally different supply chains; differences of importance to military decision makers. Fuel is a commodity supported by a global network of sources, refineries, and logistics that exist largely outside of the military. Across a wide range of security events, access to fuel is almost certain and the distance only as far as the nearest DLA-E contracted or civilian refinery. While it may have to be purchased at an elevated price, the large world supply will likely be able to support short-term military demand spikes without the need for preparatory resource hoarding. On the other hand, the hellfire design is owned mostly by Lockheed Martin, which has the proprietary right to manufacture.[21] Even if subcontracted, manufacturing Hellfires requires specialized manufacturing equipment, probably only possible in a handful of facilities which may necessitate long shipping lines depending on where they are needed. Shipping over long lines increases the chances for unexpected events and can consume considerable fuel (possibly more than that required for both delivery and operation of the ATL's energy). Manufacturing facility limitations may significantly impact the ability to meet unanticipated military demand spikes (e.g., depletion of Tomahawks during the first Gulf War may have significantly impacted the DoD's strategy and capability had a second conflict occurred shortly after). Additionally, some of components of the Hellfire require resources such as rare-earth metals that are also supply limited and potentially very far from manufacturing facilities and there is some chance for the impacts of both issues to be dramatically worsened during a future conflict. Lastly, even if the need for Hellfire missiles is properly forecasted, the preparatory build-up requires storage.

[21] In the past, Boeing acted as a secondary supplier for Hellfires and Lockheed Martin manufactured the Longbow variant [101], [102].

Moving these missiles to storage has its own costs and risks in addition to the costs and risk of keeping them there.

This analysis aimed to quantify the sometimes complex but undeniable connections between capabilities, energy demand, and logistics and how they might be dramatically impacted by a directed-energy weapon, one of many evolving technologies. Because of these connections and the reasonable possibility of inaccurately forecasting their use into the uncertain security environment and technology of tomorrow, a flexible framework that properly highlights energy-related tradeoffs for various decision makers is both critical and challenging. Incorporating these lessons and confronting this challenge, the next section introduces an expanded framework that brings capability and burdened energy and their uncertainty into the same tradespace.

6.5 Expanded Framework

This section introduces the expanded framework, which builds off the equation in Chapter 2, and incorporates expert elicitation and available data to envision a range of futures to calculate FBCE and capability. Once determined, capability and burdened energy can be compared across a range of deeply uncertain futures tailored to an analysis-appropriate resolution and presented to decision makers.

While a meaningful step forward, the previous framework has several significant limitations. First, it calculated FBCE Ratio as a function of a future, which requires that the FBCE Ratio space be recalculated every time the envisioned future changed. A future refers to the set of variables and boundaries that defines the details and critical relationships of a military operation such as geographic location, mission, end-user, logistic assets, and expected loss rates. This makes it impossible to analyze various sensitivities or compare weapon systems that exist outside of the defined boundaries but have capability overlap. By capability, we mean a weapon system's ability to conduct a mission in a particular environment against or despite a particular opponent. Following guidance in DoD Joint Publication 1, a mission "entails a task, together with the purpose, that clearly indicates the action to be taken and the reason therefore" [82]. A task is a "clearly defined action or activity assigned to an individual or organization. It is a specific assignment that must be done as it is imposed by an appropriate authority" [82]. Second, there was no direct incorporation of weapon system capability, some of which is a function of energy.

Putting the FBCE distribution in the same tradespace as capability requires a few additional steps. First, a set of weapon system choices and a list of critical JCAs for these systems are generated. Second, a range of futures plausibly requiring these weapon systems and JCAs is developed. A future defines a plausible tomorrow that scopes many modeling attributes such as logistic options and abilities, escort need and value, and overall risk. It also determines the correlations between the distributions of energy demand, logistic burden, and escort burden. Third, available data and expert elicitation is used to translate capability to effectiveness for each of these system, future, JCA combinations. Next, FBCE distributions are determined in each plausible future using a revised form of the equation from Chapter 2 across the range of the same system, future, JCA combinations. This is referred to as the FBCE Space. Depending on the comparison, the systems and their resulting combinations may not have complete overlap. In other words, one system may be limited to a different but overlapping subset of the entire space. Finally, a tradeoff frontier is created where there is JCA overlap by combining the effectiveness and FBCE distributions for each system. Across the range of futures assessed, each system's effectiveness and FBCE distributions across common JCAs are combined and compared against the same JCA combination of other choices. At the end or at any stage of the process, the results may suggest returning to any earlier stage for refinement. An overview of this process is shown in Figure 6.5, where there are *m* JCAs for *n* weapons systems, *W*, compared across the FBCE Space, *S*, with *p* futures.

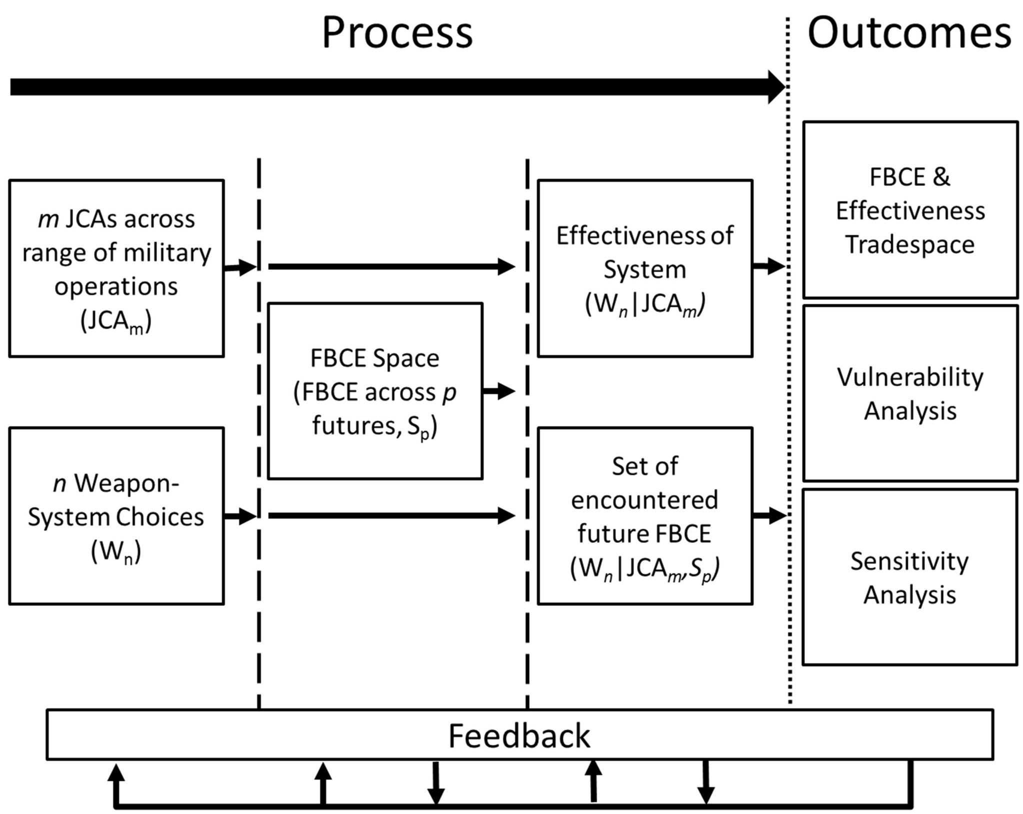

Figure 6.5: General Framework

Critical to explaining the framework, the next section gives some additional information on JCAs.

6.5.1 Joint Capability Areas

JCAs are an important component of the framework as they create a common language that allows capabilities to be defined and effectiveness elicited across a range of weapon systems and operations. The DoD defines them as “collections of like DoD capabilities functionally grouped to support capability analysis, strategy development, investment decision making, capability portfolio management, and capabilities-based force development and operational planning” [83].The JCAs translate the basic functions for a range of operations into specific tasks and subtasks with dimensions, measures, and metrics [84]. For example, basic functions include force support, battlespace awareness, force application, logistics, command and control, net-centric, protection, building partnerships, and corporate management and support. For example, the task to maneuver to engage via air is a subtask of maneuver to engage, which is a subtask of maneuver, which is a subtask of force application. Maneuver to engage via air is defined as “the ability to maneuver to engage in the region beginning at the upper boundary of the land or water and extending upward to the lower boundary of the Earth’s ionosphere (approximately 50 km)” [84].

The JCAs are the culmination of over a decade of organization shift by the DoD. The 2001 Quadrennial Defense Review introduced the desire to shift to planning with a capabilities-based approach rather than a threat-based defense planning model [85]. Then in 2004 the Joint Defense Capabilities Study Team published an independent capabilities report [86]. This resulted in the DoD dividing the department’s capabilities into functional categories and the development of the first series of JCAs, which were later refined [83], [87]. Capabilities-based approaches have been used to highlight strategies with flexibility, adaptiveness, and robustness [88], [89].

With the terminology necessary to recognize and discuss common capabilities across systems, the next section highlights the changes to the Chapter 2 equation that are necessary before incorporating it into this expanded framework.

6.5.2 Revisions to the Previous Equation

Before it can be incorporated in the expanded framework, Equation 2.1 is adjusted as shown:

$$\boldsymbol{FBCE}\ (\boldsymbol{D},\boldsymbol{L},\boldsymbol{F}) = n_e\boldsymbol{g_e}\boldsymbol{\alpha_2} + \{n_L\boldsymbol{g_L}\boldsymbol{\alpha_2} + c_L\alpha_3\} + \left(n_f\boldsymbol{g_f}p\boldsymbol{\alpha_2} + c_f\alpha_5\right) \quad \textbf{6.12}$$

The definition of the terms is similar to the introduction in Chapter 2 but the function relationships are adjusted to the new independent variables. The number of end-users required, n_e, and consumption per mission, g_e, are a function of the system and JCA. The number of logistic assets, n_L, consumption per mission, g_L, and conversion factor two, α_2 are functions of end-user demand and logistic burden.[22,23] The number of logistic assets lost, c_L, is a function of the logistic probability of loss, which is a dependent on logistic and escort burden. Conversion factor three, α_3, is determined by logistic assets used to meet the end-user demand. The number, n_f, consumption, g_f, and protection proportion, p, are functions of the logistic and escort burden. Finally, the number of escort assets lost, c_f, is a function of escort probability of loss, which is dependent on escort burden. Bolded terms are distributions. Additionally, besides those mentioned, all distributions are functions of the future in which they are calculated.

Refined through analysis and available data, the new equation has several important changes from the previous. First, the conversion terms in the new equation are simplified. During earlier analysis, α_1 and α_4 were usually highly dependent on α_2 and difficult to differentiate

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[22] Logistic asset consumption per mission is currently modeled using large fuel trucks but can be adapted as appropriate [81], [103]–[106].

[23] Logistic and escort consumption are calculated in a way that accounts for energy consumption during delivery [107].

from that term accurately because of data limitations. Because of our goal of creating a first-order metric to guide further analysis, these conversion factors have all been absorbed together. Second, future-dependent factors are absorbed directly into variable specific distributions, resulting in the FBCE Space once evaluated across a range of futures. The FBCE Space is explained in the next section. This makes the task of assessing future dependency possible. Third, while end-user demand remains, risk- dependent distributions are now functions of the FBCE Space, which includes logistic burden, L, and escort burden, F. Because the relationships between a future, its risk, logistic burden, and escort burden are no longer assumed, FBCE distributions can be calculated across a range of futures. Additionally, by removing this requirement from the framework, sensitivity to those assumptions can be evaluated. This process is explained in more detail in the next section.

Additionally, the new equation calculates FBCE instead of FBCE Ratio. In the old equation, risk-free futures with insignificant logistic demand created a FBCE Ratio of 1 across all end-user demand and systems with zero end-user demand resulted in an undefined FBCE Ratio across all levels of risk, which by convention was also defined as 1. As a result of these changes, risk-free futures with insignificant logistic demand, create a FBCE almost entirely determined by end-user demand. Systems with small end-user demand that require long, vulnerable logistic chains have a FBCE mostly comprised of logistic demand.

While it has value in certain comparisons, the FBCE Ratio systematically biases preference to options that increase end-user demand relative to the other terms (i.e., logistic and escort burden). By increasing the denominator relative to the numerator, the FBCE Ratio can give a false perception of preference for an option despite its increase in the fully burdened cost for a given capability. This consequence remains largely innocent until options with fundamentally different logistic systems are compared. Exposing this weakness is critical as the array of US military assets already contains weapon systems with overlapping capability yet that require fundamentally different logistic networks. Overlapping capability requiring further logistic differentiation is likely to grow in the future. Table 6.7 shows the Primary JCA and mission capabilities for an abridged list of unmanned aircraft in a recent roadmap [46].

Table 6.7: Excerpt of Primary JCA and Mission Capabilities from [46]

System	Lead Service	Primary JCA	Mission Capabilities
AIRCRAFT			
GROUP 1			
RQ-16B T_Hawk	US Navy	N/A	ISR/RSTA, EOD
Wasp	US Air Force	BA	ISR/RSTA
RQ-11B Raven	US Army	BA	ISR/RSTA
Puma AE	USSOCOM	N/A	ISR/RSTA, FP
GROUP 2			
Scan Eagle	US Navy , US Marines	N/A	ISR/RSTA, Force Protection
GROUP 3			
RQ-7B Shadow	US Army, US Marines	BA	ISR/RSTA, C3, Force Protection
S 100	USSOCOM	N/A	ISR/RSTA, EW, Force Protection
STUAS RQ-21A	US Navy , US Marines	BA	ISR/RSTA, EOD, Force Protection
Viking 400	USSOCOM	N/A	ISR/RSTA, EW, Force Protection
GROUP 4			
MQ-5B Hunter	US Army	N/A	ISR/RSTA, C3, Log, PS/TCS, FP
MQ-1C Gray Eagle	US Army	BA	ISR/RSTA, C3, Log, PS/TCS, FP
MQ-1B Predator	US Air Force	BA	ISR/RSTA, PS/TCS, FP
MQ-8B VTUAV	US Navy		ISR/RSTA, ASW, SUW/ASUW,
GROUP 5			
MQ-4 BAMS	US Navy		ISR/RSTA, EW, PS/TCS, SUW/ASUW, FP
MQ-9A Reaper	US Air Force	FA	ISR/RSTA, EW, PS/TCS, FP
RQ-4A Global Hawk	US Air Force	BA	ISR/RSTA, C3, PS/TCS
RQ-4B Global Hawk	US Air Force	BA	ISR/RSTA, C3, PS/TCS
MQ-X	US Air Force	FA	ISR/RSTA, PS/TCS, FP
GROUND VEHICLES			
WHEEL			
MARCbot IV N	US Army	N/A	ISR/RSTA, IED Inv.
Throwbot	US Army	N/A	ISR/RSTA
TRACK			
ISR UGV	US Navy	N/A	ISR/RSTA, Fire Support, EOD
xBot	US Army	N/A	ISR/RSTA, EOD, IED Inv.
PackBot FIDO	US Army	N/A	ISR/RSTA, EOD, IED Inv.
MARITIME CRAFT			
SURFACE			
Autonomous Unmanned Surface Vehicle (AUSV)	US Navy	N/A	ISR/RSTA
Sea Fox	US Navy	N/A	ISR/RSTA, FP
Modular Unmanned Surface Craft Littoral	US Navy	N/A	ISR/RSTA
UNDERWATER			
Sea Stalker	US Navy	N/A	ISR/RSTA
Sea Maverick	US Navy	N/A	ISR/RSTA
Large Displacement Unmanned Underwater Vehicle (LDUUV)	US Navy		ASW, ISR, MCM

As shown, there are several systems with overlapping JCAs and missions capabilities. However, because of such factors as range, these systems would have very different basing options within a potential battlespace. Any proper tradespace analysis during operations and acquisitions, including FBCE, needs to be able to compare such varying options while properly maintaining their differences.

Equation 6.12 translates a system's energy demand, logistic burden, escort requirements, their relationships, and the uncertainty in those terms and their relationships into a FBCE distribution dependent on the future envisioned. The calculation of the FBCE distribution across the range of plausible futures used for analysis is called the FBCE Space and is the subject of the next section.

6.5.3 FBCE Space

The FBCE Space is an important part of this framework and represents the FBCE distribution across the range of considered futures. It creates the opportunity to assess how the FBCE and effectiveness of different systems compare across different futures with varying impacts on capability and energy and those factors connection to logistics. This section contains justification for this part of the framework and some of the critical considerations when assessing it.

Attempting to forecast FBCE and capability requires appreciation of a great amount of uncertainty. In the future, the military may be tasked to accomplish a range of operations in many environments, against opponents with varying capabilities. Some examples of these far ranging operations includes: stability operations, civil support, foreign humanitarian assistance, peace operations, combating terrorism, counterinsurgency, and homeland defense [90]. Both system FBCE and the translation of capability to effectiveness are functions of these uncertain futures in addition to other uncertain factors (e.g., DoD and opponent technology development). This amount of uncertainty can quickly lead to paralysis in decision-making, especially if that process relies on predict-then-act modeling. Predict-then-act modeling relies on first generating a best guess of the future and then optimizing a strategy or policy decision for that future. If decision makers do not know or cannot agree on the model that relates choices to consequences, the most likely future, or the value or distributions for key inputs, these methods can lead to overconfidence or no decision [91]. Additionally, these methods can prevent decision makers from understanding the sensitivity of certain options to key factors and assumptions and the resiliency of afforded by others [92].

Creating the FBCE Space allows experts to work backwards and first assess a range of plausible futures without having to necessarily agree on their probability [93], [94]. After creation, using data and ellicitation, experts can filled these plausible futures with consistent assumptions, which determine each weapon system's FBCE and effectiveness distributions. Analysis across these distributions can reveal choices that perform better and mitigate energy-related risk across a range of futures. Even if they fail to expose an obvious choice, this analysis can highlight the importance of present-day uncertainty and encourage flexible strategies that limit consequences in the short-term while maintaining options further into the future when there is less uncertainty. At the very least, it would underscore those futures, relationships, and assumptions that stress the options available. If the future begins to unfold in a way similar to a pathway that was predicted to be stressful for the choice made, the DoD could take action to limit the likelihood of it progressing or move to mitigate the consequences when it occurs. This kind of approach has been used by other decision methods, such as RAND's Robust Decision Making, to address other deeply uncertain problems [91], [95], [96].

There are many important considerations when defining the range of futures for analysis. Future resolution and future range must be carefully assessed as a function of the needs of the analysis and decision makers and the systems being compared. For each future, there is a balance between detail and robustness. Overly defining a future with detail may encourage overconfidence, an underappreciation of risk and uncertainty, in elicited experts' opinions, and result in a future with an almost zero probability of occurring. Too much uncertainty may create an overly fuzzy or ill-defined future that makes elicitation impossible or unreliable or generates opinions so far ranging that it nullifies the value of comparison to decision makers. Enough range across futures must be created so each system's uncertainty can be assessed, compared, and translated to decision makers. Properly analyzing uncertainty can highlight options that with less sensitivity and increase the probability that the tradeoff frontier of FBCE and effectiveness distributions includes the actual encountered. However, attempting to determine an exhaustive range of futures is cognitively difficult and potentially expensive.

Additionally, the capabilities of each system being compared needs to be carefully assessed. JCA and system combinations will not need to consider certain futures if their probability of employing that capability is negligible even if that future is encountered. For similar reasons, within the range of the FBCE Space, enough resolution must exist to differentiate the system, JCA, and future combinations. However, too much future detail can create additional work with little value when comparing the weapon systems.

Within each and across all futures considered, data should be used when available. However, care should be taken to acknowledge the probability of predictive failure whether this space is filled with data or expert elicitation or both. As described earlier, estimating future energy burden critically depends on several very uncertain factors such as the future security environment and technology. Any amount of data cannot perfectly reflect the trends of tomorrow, especially if some combination of events has yet to occur or hasn't occurred in a considerable time, creating time for a multitude of other factors to have fundamentally changed. In a similar sense, it is unlikely any expert can accurately forecast what international events will happen, where technology will be at that point, and how these factors influence each other as they impact military energy burden and capabilities.

6.5.4 An Illustrative Example

This section provides an explanatory example intended to aid understanding of the detailed example in the next. An illustrative example of the FBCE Space's range and resolution is shown below in Figure 6.6.

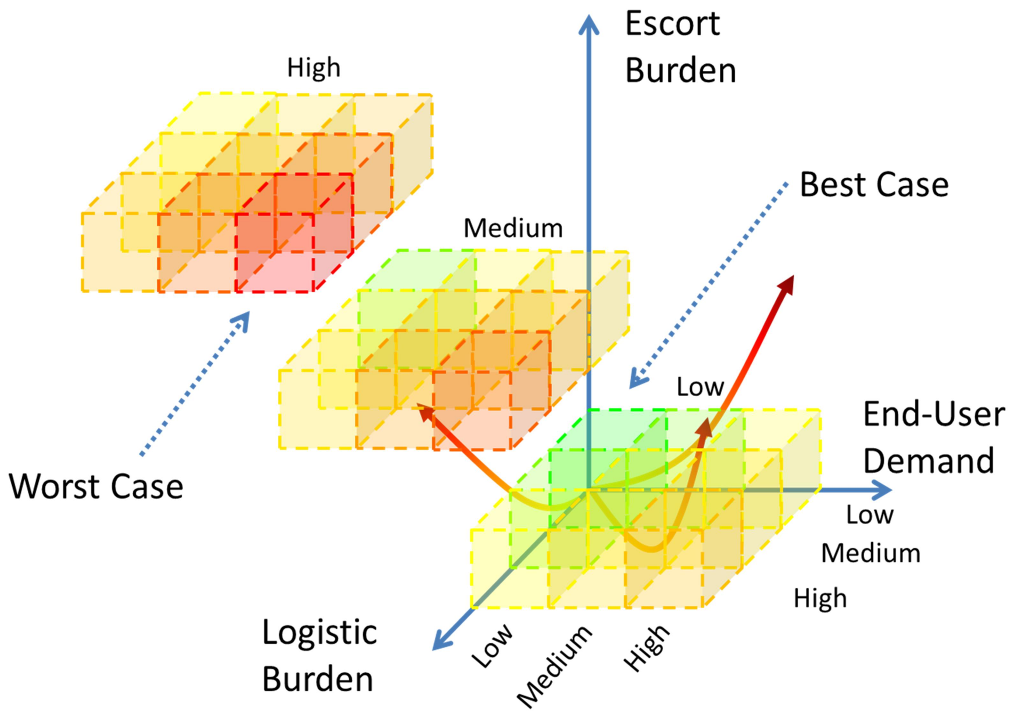

Figure 6.6: FBCE Space

As shown, this space is discretized into 27 cubes or futures. Depending on the needs of the analysis and the systems being compared, this may be too much or too little. The space can be divided as necessary or assessed continuously. Each future's definition changes the relationships between end-user demand, logistic burden, and escort burden. Altering these relationships, changes the future's placement in the space and the calculation of FBCE for any system in that future. As illustrated, FBCE grows non-linearly from the origin. Accordingly, there is a natural preference on location within the FBCE Space for discussion purposes. However, the attributes that determine location are not all controllable. Some attributes of best-case futures might include short, safe, sea-assessable logistic networks removed from a well-defined battlefront against a low capability opponent (e.g., non-existent intelligence services and an inability to challenge air and sea dominance). Some attributes of worst-case futures might include long, high-loss, land-locked logistic networks against a high-capability, near-peer opponent. Additional example descriptions of possible futures within this space are contained in Table 6.8. Again, this must be amended as a function of the analysis, experts, and systems.

Table 6.8: Future Examples

End-User Demand, Logistic Burden, Escort Burden	Example of Defining Characteristics
Low, Low, Low	Humanitarian Relief with perfect, all-inclusive, real-time intelligence for a sea-assessable location closely with short, robust logistic chains
Low, Low, High	Irregular warfare against state or non-state actors with perfect, all-inclusive, real-time intelligence (yours contrary) in a sea-assessable theater with short but vulnerable logistic chains
Low, High, Low	Humanitarian Relief with flawed, spotty, and/or delayed intelligence for a land-locked location with long, failure prone logistic chains
Low, High, High	Irregular warfare against state or non-state actors with perfect, all-inclusive, real-time intelligence (yours contrary) in a land-locked theater with long and vulnerable logistic chains
High, Low, Low	Traditional warfare against less powerful, nation state with flawed, spotty, and/or delayed intelligence (yours contrary) in a sea-assessable theater with short and invulnerable logistic chains
High, Low, High	Traditional warfare against near-peer, nation state with perfect, all-inclusive, real-time intelligence (yours contrary) in a sea-assessable theater with short but vulnerable logistic chains
High, High, Low	Traditional warfare against less powerful, nation state with flawed, spotty, and/or delayed intelligence (yours contrary) in a land-locked theater with long but invulnerable logistic chains
High, High, High	Traditional warfare against near-peer, nation state with perfect, all-inclusive, real-time intelligence (yours contrary) in a land-locked theater with long and vulnerable logistic chains

After defining the space and enough future consistent assumptions, a FBCE distribution is calculated through Equation 6.12. An illustrative representation of this process is shown in Figure 6.7.

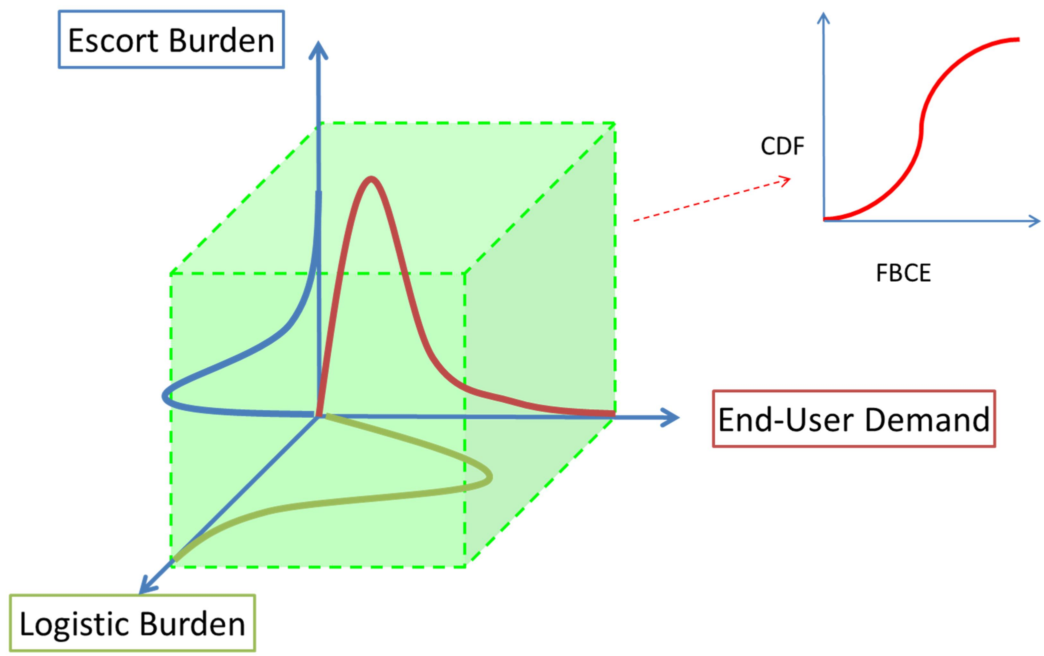

Figure 6.7: FBCE Space Cube

As mentioned, while the FBCE space is determined independently of system, mission, and operational factors, a weapon system's location is not. The location within the space is determined by the logistic burden incurred by a weapon system to achieve a JCA in an operation with elicited effectiveness.

An abbreviated list of factors to consider is shown in Table 6.9. These factors are not deterministic a priori nor completely controllable a posteriori. Accordingly, there may be multiple FBCE futures possible for a single weapon system to accomplish a particular JCA. Additionally, while some positive measures can be taken before and during operations to reduce the chances of encountering less desirable FBCE, the one encountered is not completely controllable. In the end, this means that FBCE, by itself and along with effectiveness, represents both a vulnerability to the military and an opportunity. For example, the existence of an opponent creates a reflexive factor space, whereby one's location in the FBCE space is not only a function of some uncertain and uncontrollable factors but also one's opponent.

Table 6.9: Consideration Factors in FBCE Space Location

	Low	High
	⟵	⟶
Distance	Short	Long
Event Assess	Assessable by sea	Land-locked
Req'd Mobility	Reinforce/Defense	Advance
Timeliness Req'd	Time Insensitive	Time Critical
Intel Quality	Perfect	Imperfectly Flawed
Intel Quantity	All-Inclusive	Unknowingly Unreliable
Intel Flow Rate	Real-Time	Uselessly Delayed
Opponent	None	Near-Peer

As an example, assume two weapon systems are presented at acquisition to fill a capability that is describable with a single JCA. As this is a descriptive example, assume capability effectiveness across operations is properly elicited and mapped into the FBCE space shown in Figure 6.8. As illustrated, Weapon System 1 can exist in five FBCE cubes, while Weapon System 2 can exist in two. Existing in multiple cubes represents the level of uncertainty in mapping between that weapon system's capability and FBCE. For this initial work, we are excluding the uncertainty created by the different tactical uses of the weapon system that cause capability variations within a single JCA.

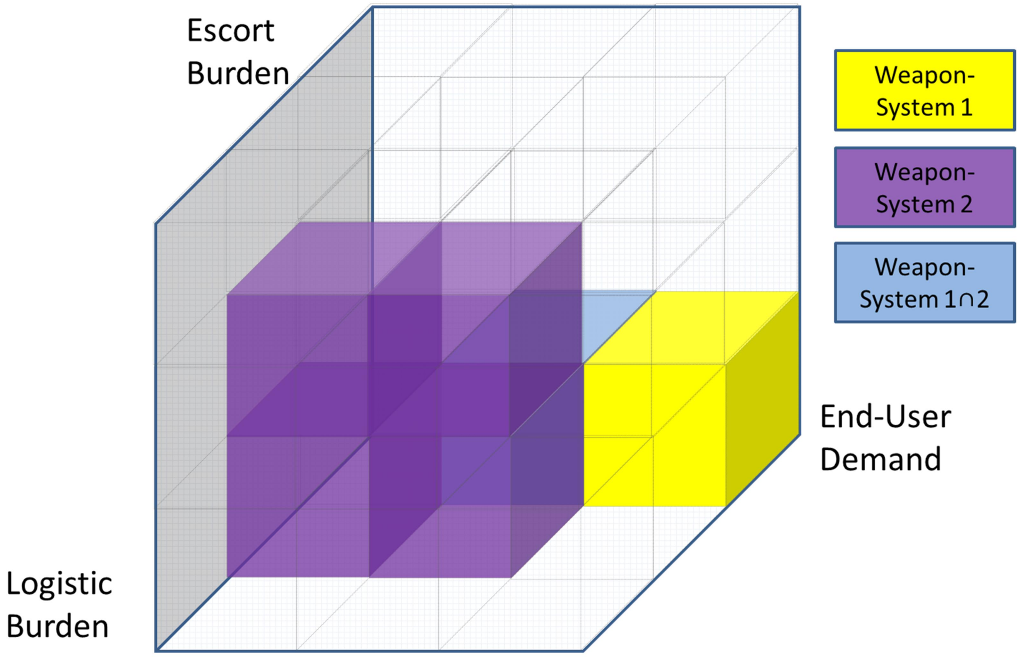

Figure 6.8: FBCE Space Example

We can perform several levels of analysis depending on the relationships between the weapon systems' effectiveness and FBCE distributions. If effectiveness parity exists, FBCE can be compared as shown in Figure 6.9. By comparing the cumulative distribution functions, decision makers could assess aspects of the burdened energy cost, such as preference between lower average costs and reduced uncertainty.

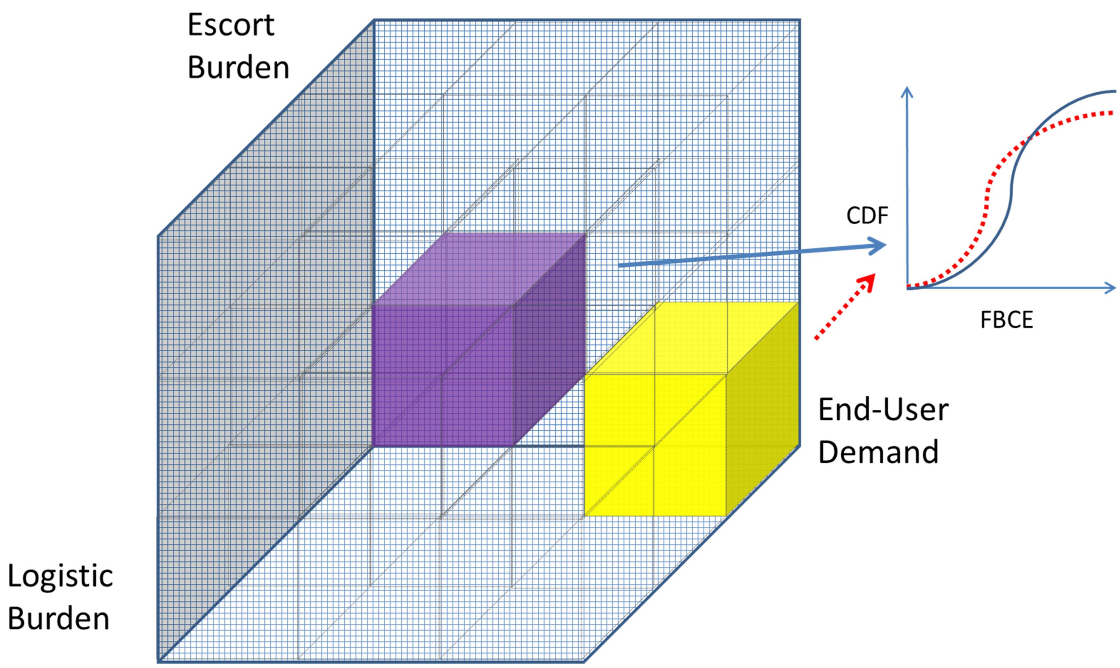

Figure 6.9: Effectiveness Parity Example

If FBCE parity exists, as in the Figure 6.10, effectiveness can be compared. While not the primary focus of this work, looking for parity also creates the opportunity to address how different distributions have to be to have value in system comparisons.

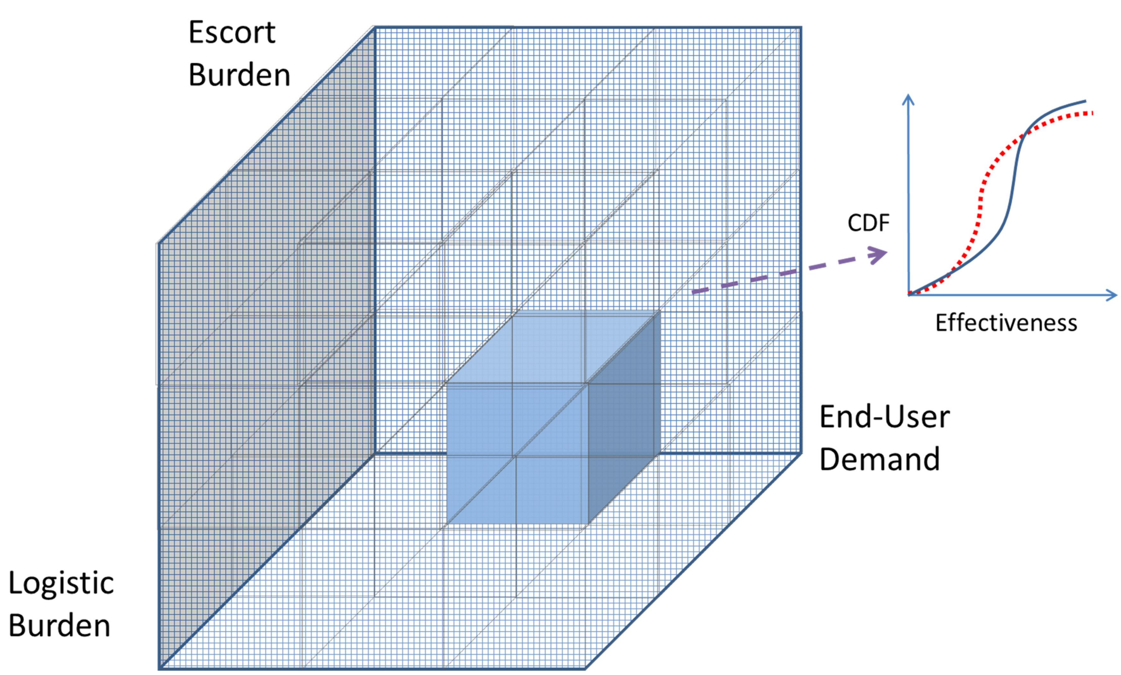

Figure 6.10: FBCE Parity Example

In the likely case that complete parity does not exist, a graph of effectiveness versus FBCE can be created. Figure 6.11 shows several examples of this tradeoff. This may create a number of valuable insights for the decision maker. For JCA_1, weapon system 1 (W_1) has a lower expected effectiveness but significantly lower FBCE and less uncertainty in both. For JCA_2, weapon system 2 (W_2) has a dominant effectiveness distribution and a lower expected FBCE compared to 1 though at the cost of more uncertainty in both. For JCA_3, weapon system 1 dominates 2 in FBCE, has a slight higher expected effectiveness, and less uncertainty in both. Better expected values for FBCE and effectiveness save lives, money, and resources and create more capable weapon systems on average. Reducing uncertainty makes contingency planning easier.

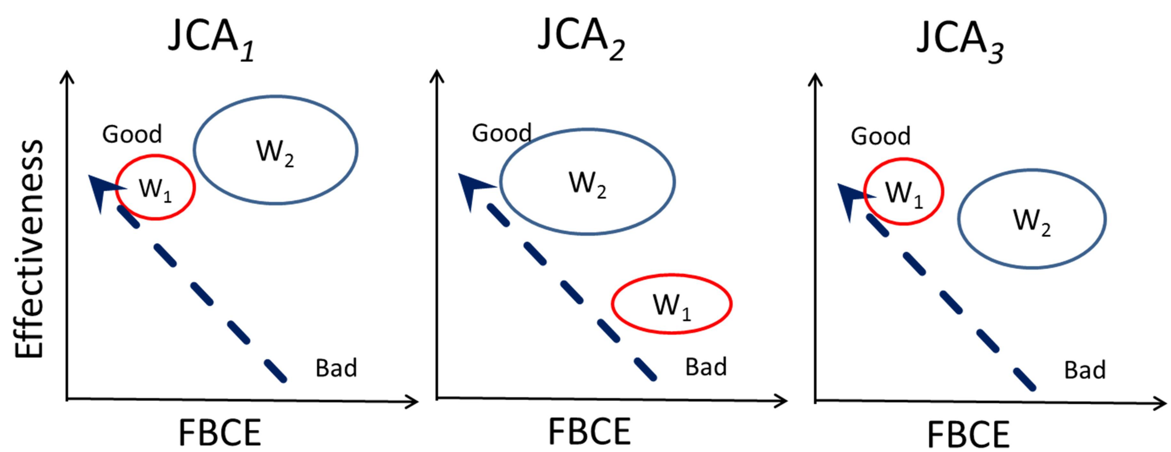

Figure 6.11: Effectiveness vs FBCE Tradespace for Both Weapon systems

Traditional methods of viewing this space hide most of these insights from the decision maker as shown in Figure 6.12. As shown, traditional analysis eliminated uncertainty from the cost of burdened energy (A), eliminated uncertainty from both metrics (B), failed to account for capability overlap with vastly different logistic costs (C), or some combination. This prevents the decision maker from perceiving any of the before mentioned insights.

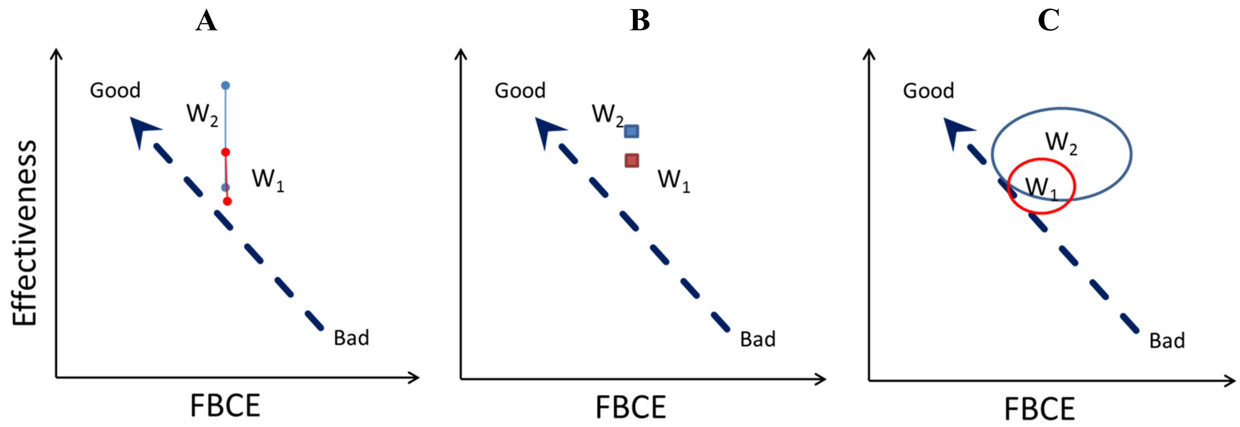

Figure 6.12: Tradespace for JCA_1 with Traditional Analysis Methods

In the next section, we present a more detailed example of this framework.

6.6 Long-Range versus Short-Range Drones

In this section, we apply the previously introduced framework to compare the FBCE and capability tradespace of two hypothetical systems, long- and short-range drones. The long-range drone's performance, energy demand, and logistic requirements are modeled after a B-2 Spirit and the short-range drone after a MQ-9 Reaper [46], [97]. The analysis forecasts FBCE, capability, and the underlying relationships into the near-term, where available data is more reliable. This time horizon could be relaxed in an attempt to understand the potential impact and uncertainty of technological innovation better. This topic is briefly discussed at the end of this section.

6.6.1 Creating the Tradeoff Frontier

The first step is to define the weapon system options and overlapping JCAs. The weapon system options were defined above. To simplify the demonstration of this framework, we assume the only JCA for both systems is to engage a soft surface target via kinetic means.

The next step to generating the tradeoff frontier is to create a range of plausible futures given the weapon choices and JCA. Depending on the needs of the analysis and decision makers, the scope must be broad enough to represent reasonably the uncertainty of forecasting future military operations and each future must be sufficiently defined for expert elicitation. With that said, the aim is not to generate an exhaustive list of every military operation that could happen everywhere in the world against every plausible opponent. There simply needs to be enough detail for data from similar enough past events to be identified and experts to postulate how in that future the military could react (e.g., what logistic networks and systems could be used, what systems might be used as escorts, and how beneficial those escorts might be).

For this analysis, any futures not requiring this JCA are eliminated from consideration (e.g., humanitarian relief). Across the remaining range of futures, end-user demand, logistic burden, and escort burden are discretized at three levels. This results in 27 futures though not all of these have to be translated into the FBCE Space because of system performance and other assumptions. For example, in the near future, neither system is assumed to be able to perform the JCA effectively in futures with near-peers.

Plausible futures are further reduced by analyzing the system-level factors and assumptions. Modeled after the B-2, the long-range drone is assumed to be an exceedingly high-value asset. In combination with its range, none of the futures considered create reasonable justification for putting it at risk by basing it close to the battlefield. Accordingly, the long-range bomber creates a large end-user demand, though this is met with usually short logistic networks relatively safe from most opponents considered. As a result, the long-range drone exists in only a subset of the future space considered. Large end-user demands increase uncertainty and its impacts about that axis. However, its usually short and sheltered logistic networks are unlikely to require escorts, greatly reducing uncertainty and simplifying futures considered along the other two axes.

In contrast, the short-range drone requires deployment closer to the target. Because of its size and placement, the short-range drone has a much lower energy demand. However, logistic chains have to deliver that energy over a much longer distance. This necessitates appreciation of futures with more uncertain logistic networks that are generally more burdened (e.g., consuming a larger portion of more expensive energy per gallon). On average, these logistic networks are also much more vulnerable and usually require escorts and their associated costs. The vulnerability of logistic and escort assets and the protective value of escort assets are uncertain functions of the short-range drone's subset of futures.

For the remaining futures, Equation 6.12 calculates the FBCE Space through Monte Carlo analysis. Across the systems and futures, Latin hypercube sampling is used with a common random number seed. Distributions are modeled as log normal. This is done to restrict the random variables to positive values and to cause additional uncertainty across futures to predominately extend the upper tail of each distribution. For example, if the mean fuel-per-mission increases so does the time aloft and chance for impact from such factors as weather and mechanical issues. Accordingly, higher fuel-per-mission distributions have more uncertainty and longer upper tails. Given the illustrative intent of this example, formal expert elicitation was not conducted. Distributions and the relationships of distributions in the FBCE Space futures are based on available data and assumptions. For example, given a future, the mean probability of loss for logistic assets is assumed to increase with the number required but the marginal change decreases. The same is assumed for the protective value of escort assets. At first, the future is assumed to bound the amount of uncertainty in the distributions and relationships. Later, sensitivity analysis is conducted so the significance of this assumption can be tested.

For its subset, the long-range bomber has a consumption distribution mean ranging from 6,000 to 12,000 gallons per mission. Futures with basing towards the edge of system range require logistic networks with significantly larger capacity. However, FBCE is relatively insensitive to this given the usually short, low-risk supply chains. These supply chains have a mean distance of 25 miles and a mean escort of zero assets per logistic vehicle. For its subset, the short-range bomber has a consumption distribution mean ranging from 300 to 700 gallons per mission. The required one-way distance for logistic networks ranges from 300 to 1,000 miles with a mean of 600 and an allocated escort distribution mean of one. In the figures that follow, the long-range drone is system 1 and the short-range is system 2. Figure 6.13 shows the low and high FBCE boxplots for each system across the FBCE Space. The figure shows the 25th to 75th percentile boxed with the median marked by the center line, mean represented by a plus sign, and whiskers out to the 10th and 90th percentiles.

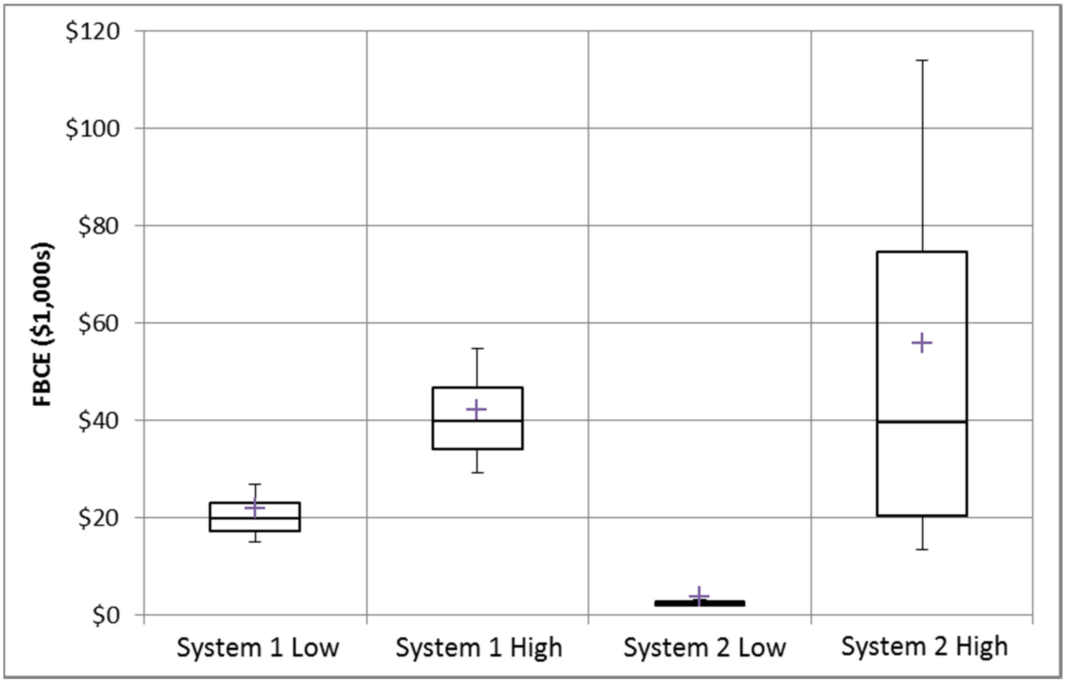

Figure 6.13: Boxplot of Low and High FBCE Across the FBCE Space

For system 1, the bounding FBCE distribution futures are at the ends of its assumed performance. The minor increase in risk and logistic burden from being closer to the target is outweighed by the significant decrease in mean and uncertainty of fuel consumption. In contrast to system 1, the short-range drone is relatively insensitive to its own demand and much more impacted by the logistic and escort burden resulting from that demand. System 2 is most sensitive to escort burden and its future-dependent relationship to logistics and risk. More specifically, system 1 is most sensitive to the cost per gallon of energy and system 2 to the probability of escort loss.

Next, the expert elicited effectiveness distributions for each section of the FBCE Space are assumed as symmetric triangle distributions. It is assumed that the quantity of uncertainty present in the future and FBCE's sensitivity to that uncertainty directly impacts the median and spread of effectiveness. Additionally, it is assumed that the long-range bomber's effectiveness is slightly less impacted by this uncertainty because it is a higher cost system with better avionics. Figure 6.14 shows the tradespace for the low-high futures for both systems. The intersections of distributions' medians are shown as a diamond and square for system 1 and 2, respectively. The intersections of distributions' mean are shown as with an "x" and the error bars represent the 10th to 90th percentiles.

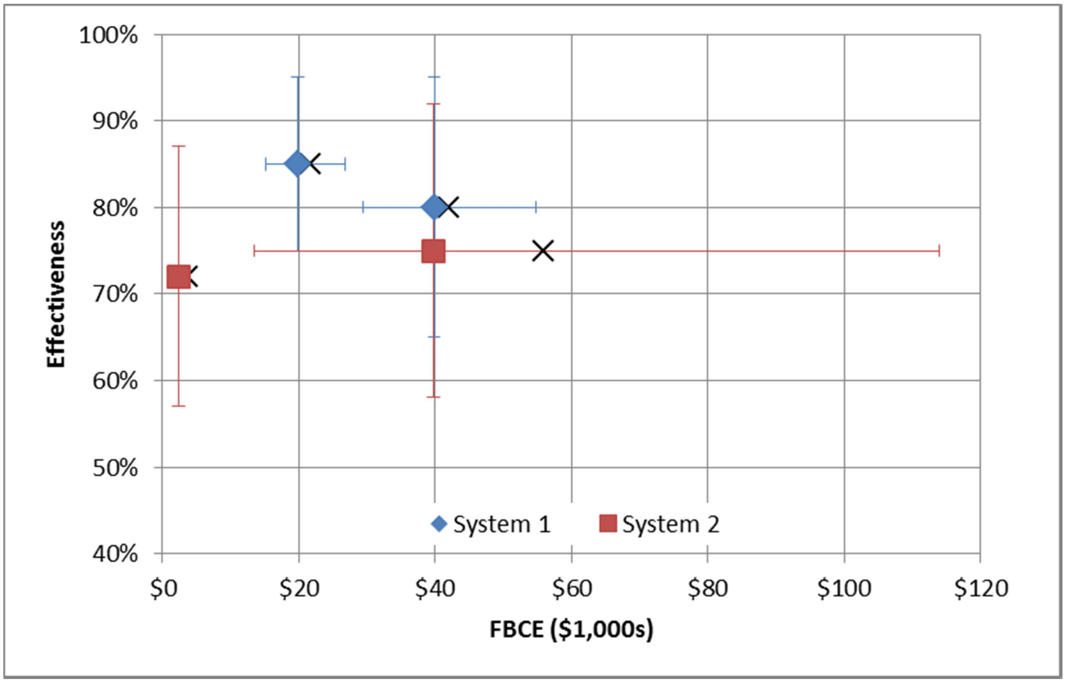

Figure 6.14: Effectiveness and FBCE Tradespace for Low-High Futures

Averaging the medians, means, 10th percentiles, and 90th percentiles of all futures in the FBCE Space for each system results in Figure 6.15. This tradespace may be helpful for a decision maker to appreciate the average relationship between FBCE and effectiveness. As shown, the short-range drone has a lower FBCE median and effectiveness on average and considerably more uncertainty in both.

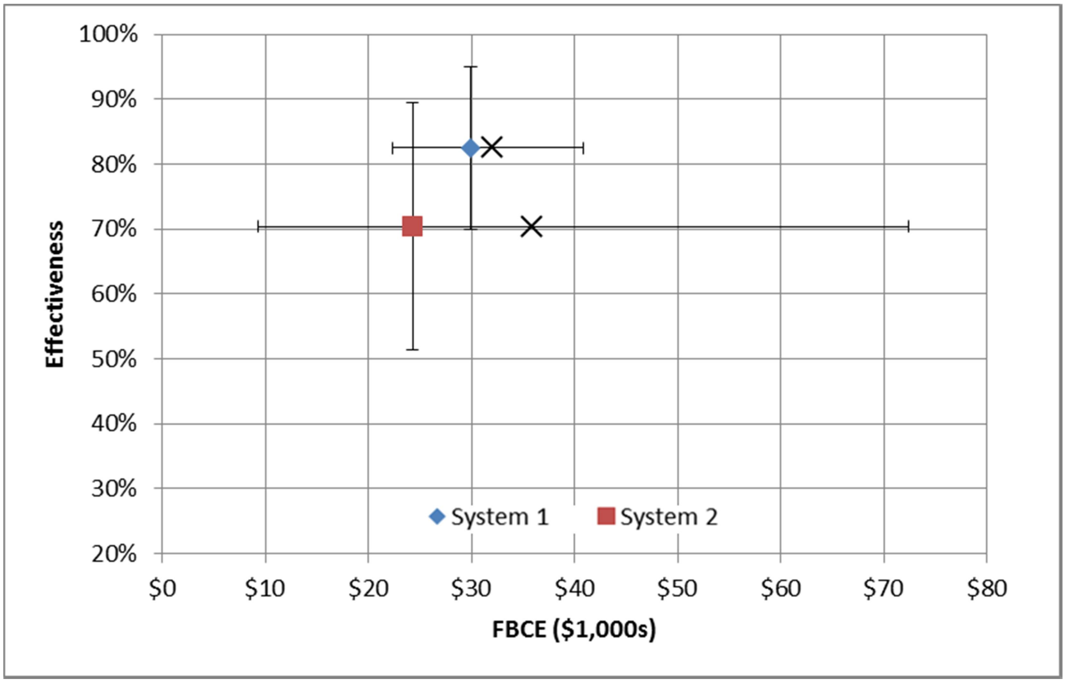

Figure 6.15: Effectiveness and FBCE Average Distribution Across All Futures for Systems 1 and 2

Figure 6.16 shows the same average of medians and means with the error bars depicting the minimum 10th percentile and maximum 90th percentile. This tradespace may be helpful for a decision maker to appreciate the plausible range of the relationship between FBCE and effectiveness. With either of these, a decision maker can evaluate system options as they compromise between such attributes as better median effectiveness for worse median FBCE or less certain but lower FBCE average for more certain but higher FBCE average.

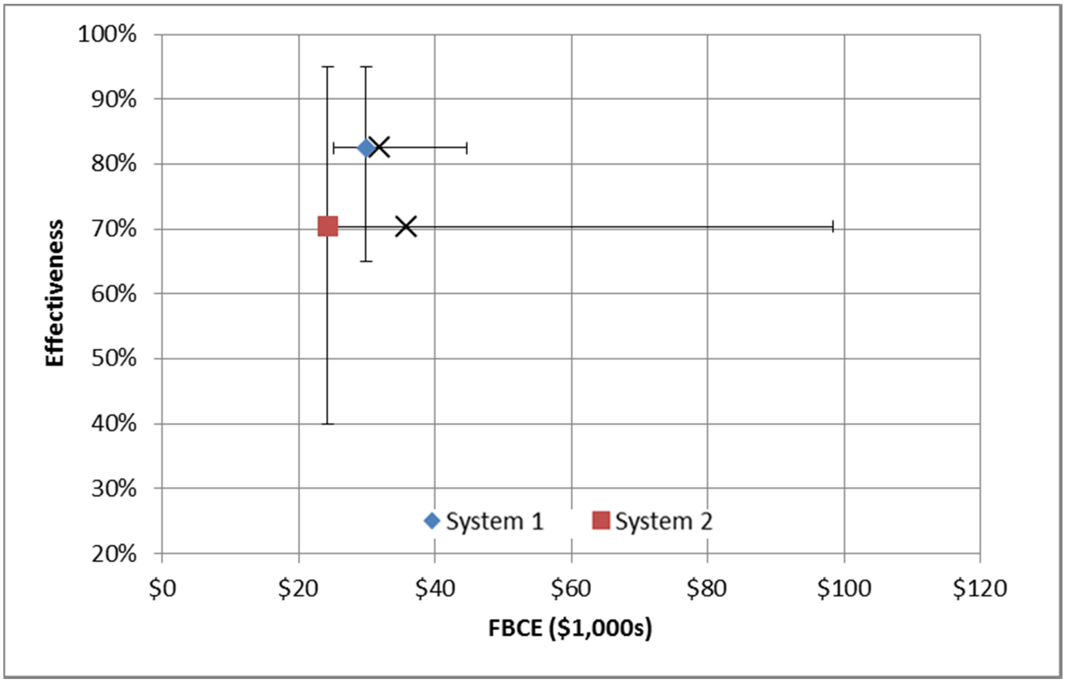

Figure 6.16: Effectiveness and FBCE Distribution Spread Across All Futures for Systems 1 and 2

As mentioned, none of these comparisons are possible with FBCE Ratio because the long- and short-range drones exist in futures with different logistic requirements. The same results as above are recreated for FBCE Ratio in Figure 6.17, Figure 6.18, and Figure 6.19.

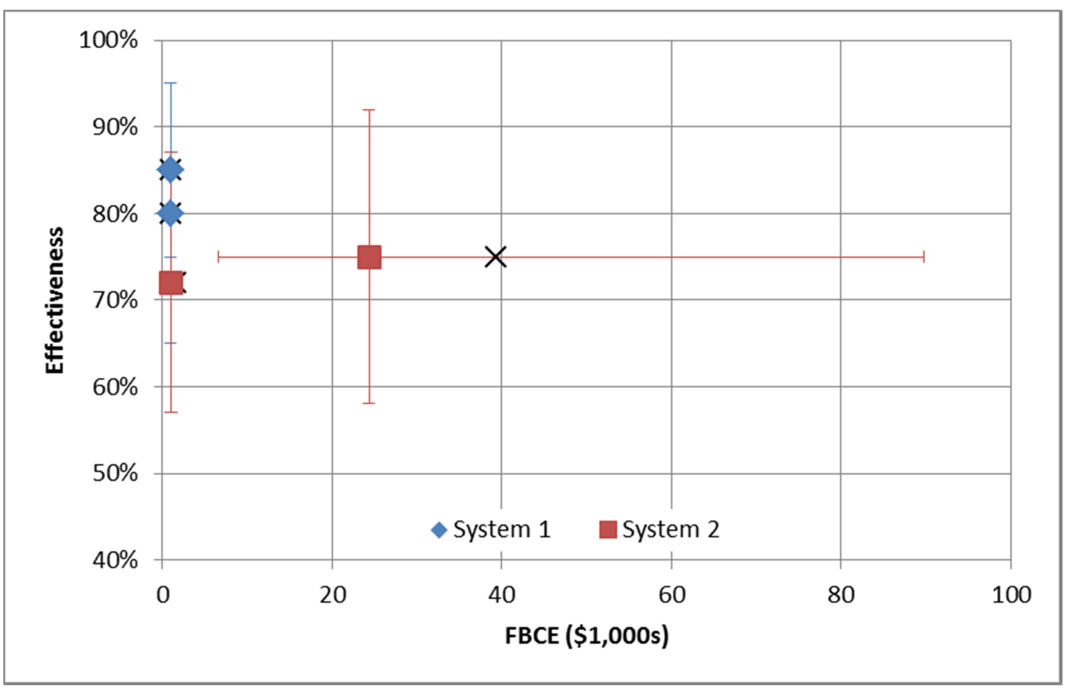

Figure 6.17: Effectiveness and FBCE Ratio Tradespace for Low-High Futures

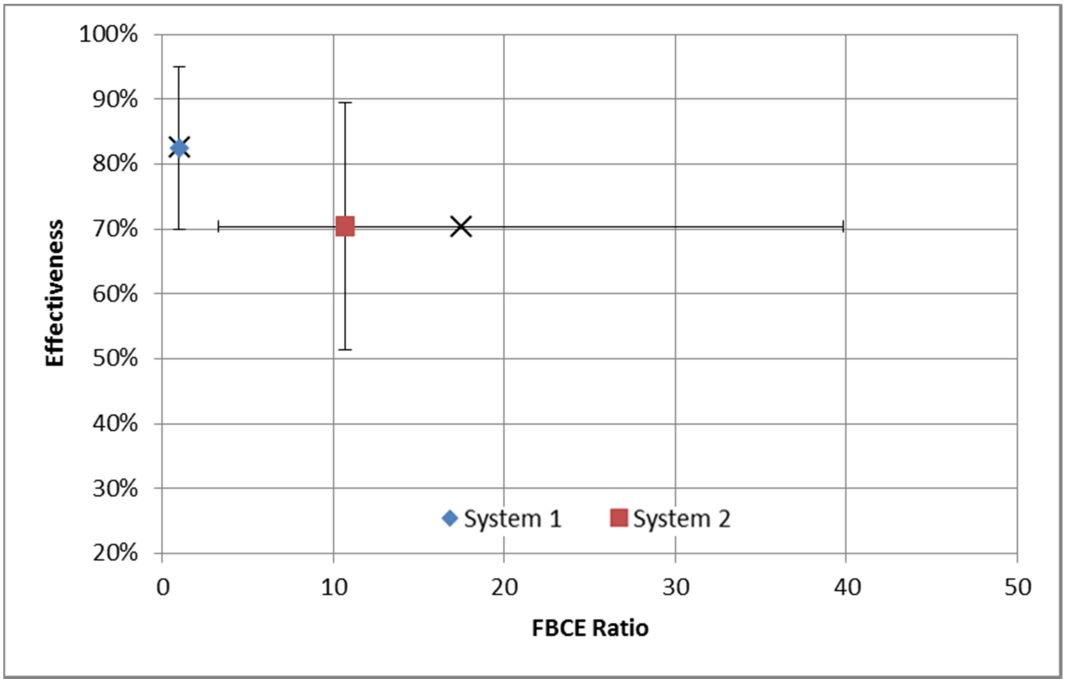

Figure 6.18: Effectiveness and FBCE Ratio Average Distribution Across All Futures for Systems 1 and 2

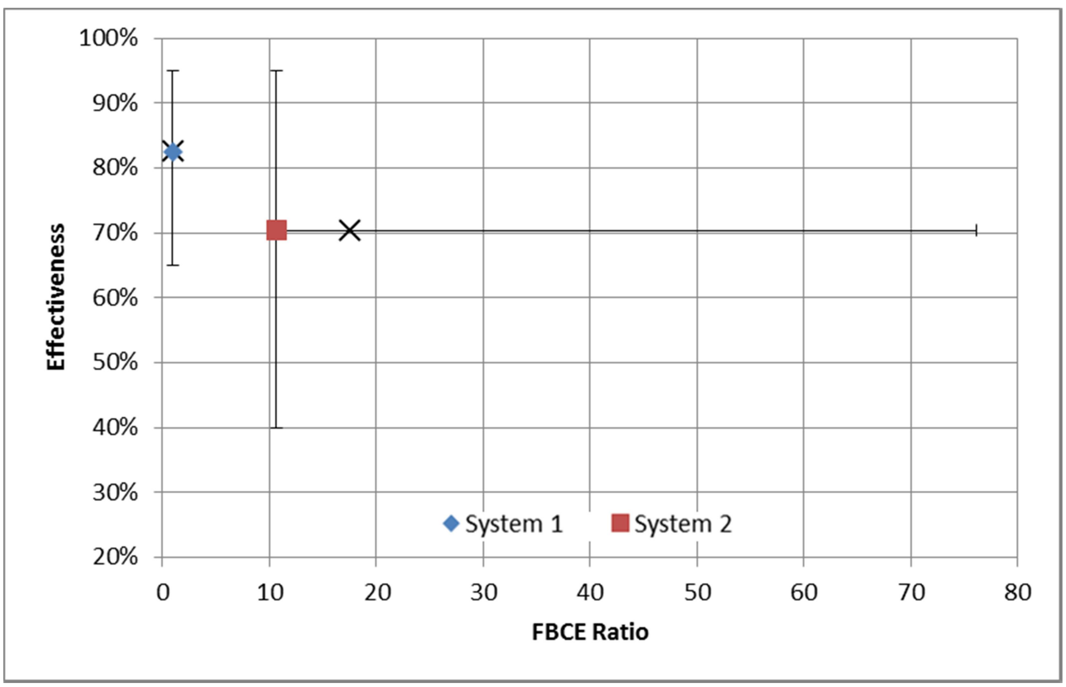

Figure 6.19: Effectiveness and FBCE Ratio Distribution Spread Across All Futures for Systems 1 and 2

6.6.2 Sensitivity and Vulnerability Analysis

Besides creating a decision maker tradespace, this framework presents the opportunity for sensitivity and vulnerability analysis. In the FBCE high future, system 1 is most sensitive to energy costs. This holds for all futures considered. However, system 2 sensitivity is more future dependent. In most futures, it is very sensitive to the probability of loss, either logistic or escort asset loss. However, when the overall risk falls below a certain threshold in some reasonable percentage of futures, system 2 is more sensitive to logistic burden factors, such the efficiency and size of the network. Accordingly, system 1 is an option with less sensitivities to monitor but system 2's sensitivities may be more directly controllable.

This framework also allows uncertainty to be incorporated into the FBCE Space mapping and the underlying assumptions of the relationships between energy demand, logistic burden, and escort burden. This analysis can reveal option vulnerability to prediction or modeling inaccuracies or the consequences from opponents or other outside factors exacerbating logistic issues. As shown in Figure 6.20, both systems have some sensitivity to mapping with both 90th percentiles growing. However, system 1 is clearly more impacted. Interestingly, the reduction in average median FBCE slightly outweighs the spread of the 90th percentile.[24]

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[24] Figure 6.20 is built from a Monte Carlo run that simultaneously calculates mapping uncertainty in all axes of the FBCE Space. Performing the sensitivity analysis one axis at a time is easier to interpret. However care should be taken as the impacts of mapping uncertainty are superadditive.

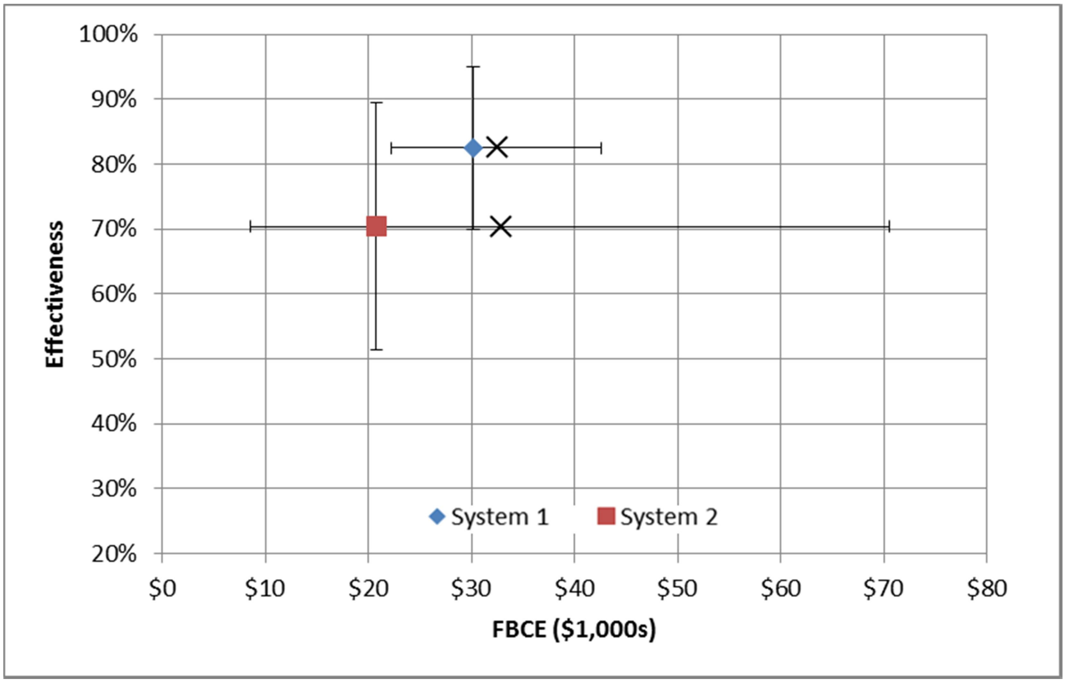

Figure 6.20: Average Distribution Across All Futures for Systems 1 and 2 with Mapping Uncertainty

The framework also allows the uncertainty to be incorporated into the assumed relationships (e.g., the connection between energy demand and logistic networks, the number of logistic assets and probability of loss, and the protective value of escorts). This allows those options more sensitive to these assumptions, especially uncertain ones, to be identified for decision makers. Figure 6.21 shows the results of incorporating uncertainty into all modeling relationships simultaneously. As illustrated, the descriptive statistics for both systems are appreciably impacted by this additional uncertainty though system 2 is noticeably more so.[25] If performed in a more systematic fashion, particularly sensitive relationships could be identified. Depending on the relationship, analysis could then focus more resources there to improve

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[25] For both systems, the quantity impact to the FBCE distribution is greater the further the future is from the best case shown in Figure 6.6. However, the percent impact to the distribution is greater the closer the future is to that case. It is unclear which creates more challenges for contingency planning. As mentioned earlier, fuel expenditures represent a relatively small portion of total DoD budget but overspending has appreciably impacted operations in the past. [1], [11], [12]

confidence in the assumptions taken. Additionally, across multiple analyses, common vulnerabilities may be noticed allowing time for contingency planning in case this future relationship becomes more likely.

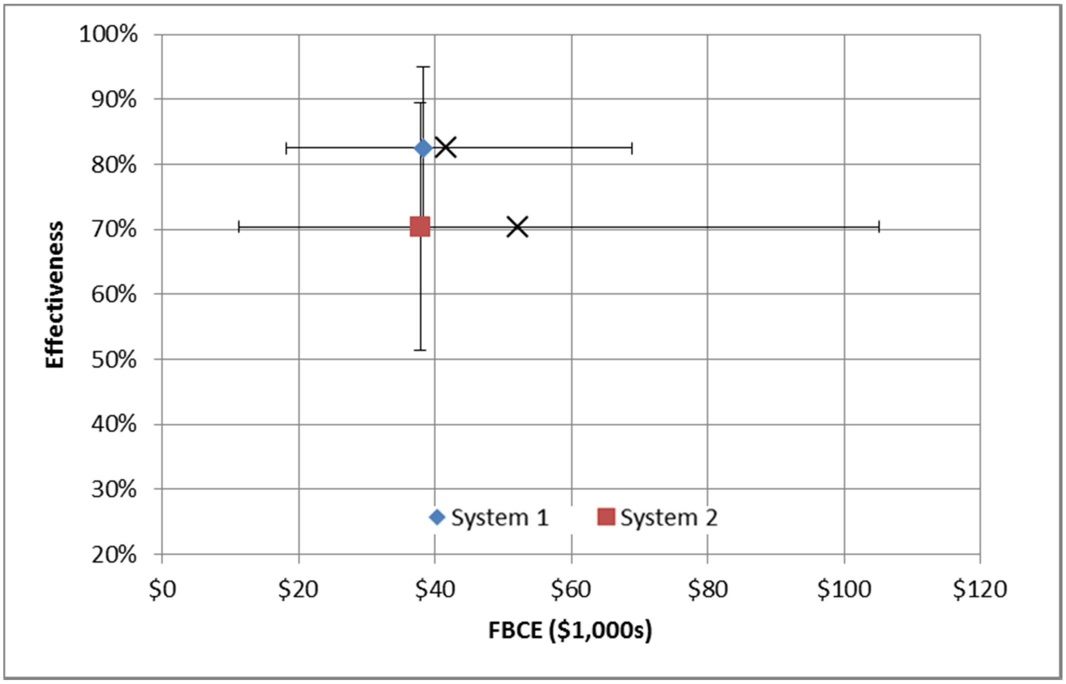

Figure 6.21: Average Distribution Across All Futures for System 1 and 2 with Relationship Uncertainty

The next section highlights an additional tradeoff possible through this framework.

6.6.3 Goal Seek Optimal Escorts to Minimize Mean FBCE

This last section conducts addition analyses on the relationship between logistic and escort burden for system 2, the short-range bomber. Following initial analysis, there is evidence of clustering across all the futures for that system. Table 6.10 shows the five basic groups and defining characteristic(s). Stochastically optimizing the number of escorts to minimize the FBCE mean for every future within each group always leads to the same the same solution. These solutions are tested with a battery of initial conditions to improve confidence in the answers.[26]

Table 6.10 System 2 Future Families and Defining Characteristic(s)

Group	Defining Characteristic	Optimal Escort Ratio
1	Low Logistic and Escort Burden	0.78
2	High Logistic Burden	4.84
3	High End-User Demand and Logistic Burden	4.48
4	High Escort Burden	0.16
5	High Logistic Burden and Escort Burden	0.31

In addition to sharing the same optimal solution, every future within each group shares a similar resiliency to suboptimal changes. Figure 6.22 and Figure 6.23 show the impact to the FBCE mean and standard deviation, respectively, as the escort ratio is moved from optimal for Group 1.

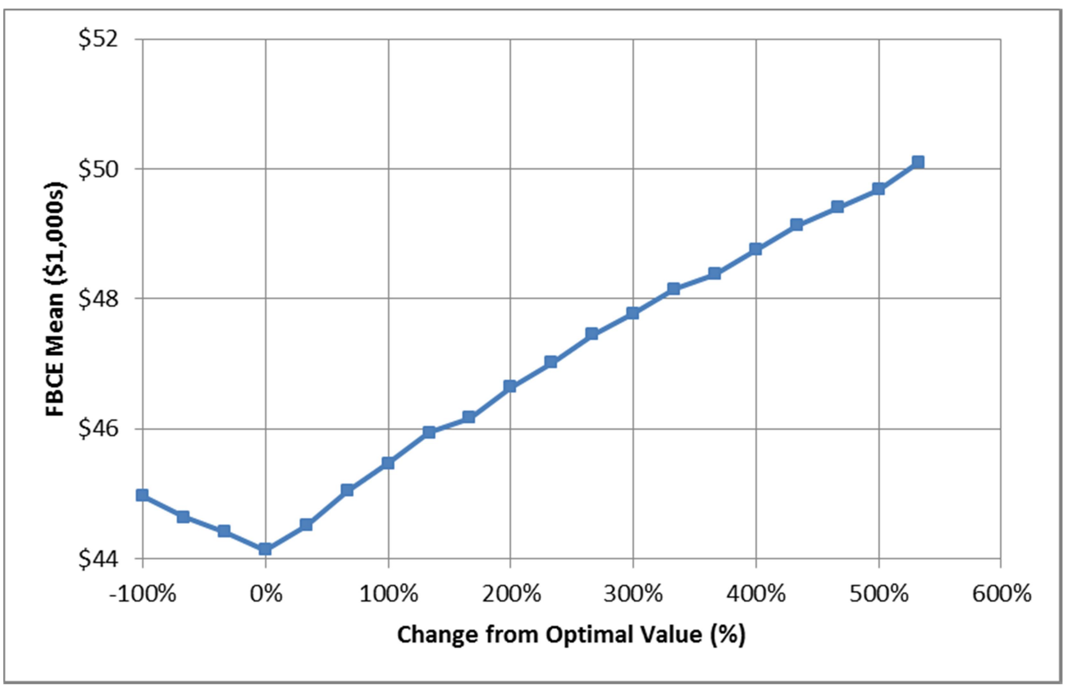

Figure 6.22: Change to FBCE Mean for Future Group 1

[26] As implemented, the framework allows non-integer escorts. Even if changed later, non-integer optima are possible because of *p*, the proportion allocation variable. For example, while it is not possible to allocate 78/100th of an escort to a logistic network, it is possible to allocate one for 78% of the route.

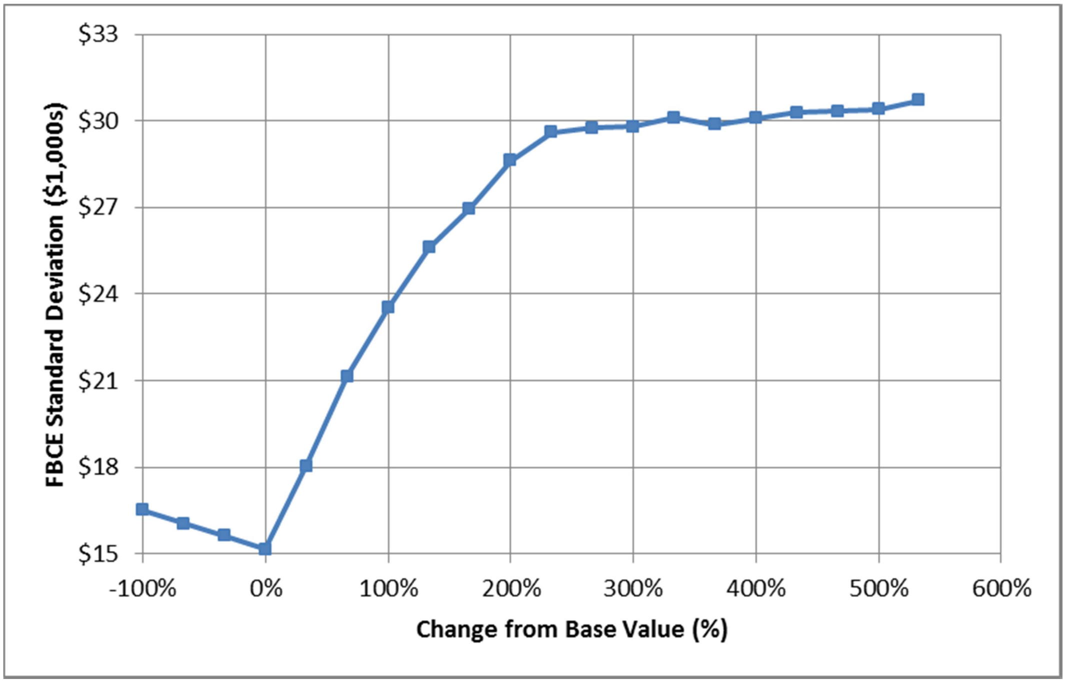

Figure 6.23: Impact of Suboptimal Change to FBCE Standard Deviation for Future Group 1

However, not all groups demonstrate this same shape and degree of resiliency. Figure 6.24 and Figure 6.25 show the percent change in FBCE mean and standard deviation as the escort ratio moves from optimal.

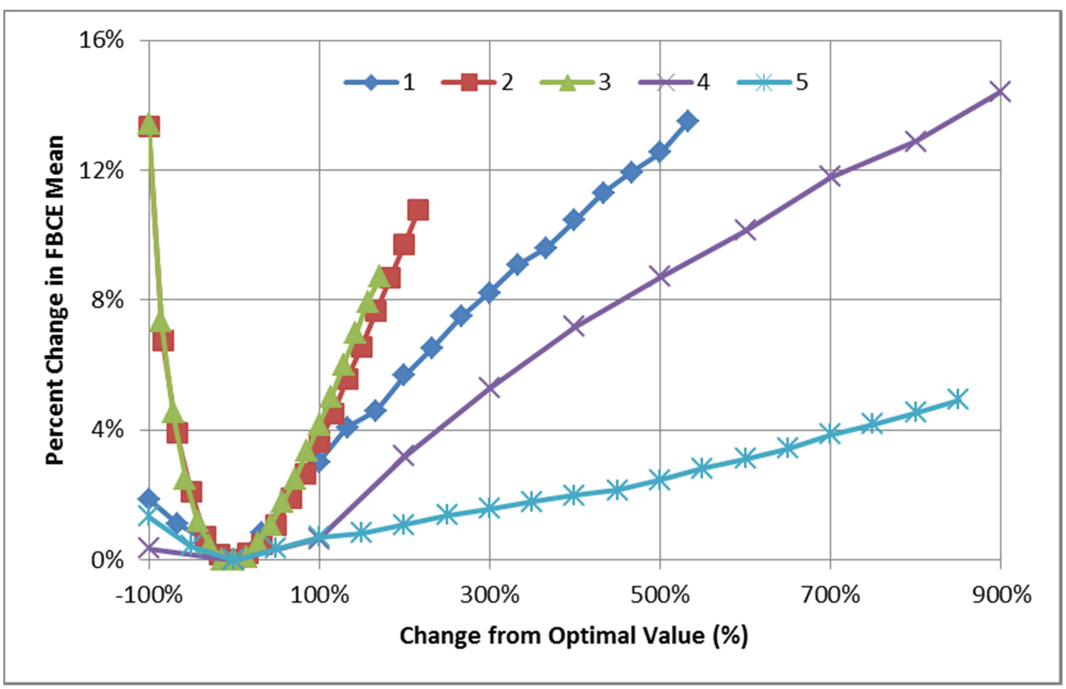

Figure 6.24: Percent Change to FBCE Mean for Future Groups

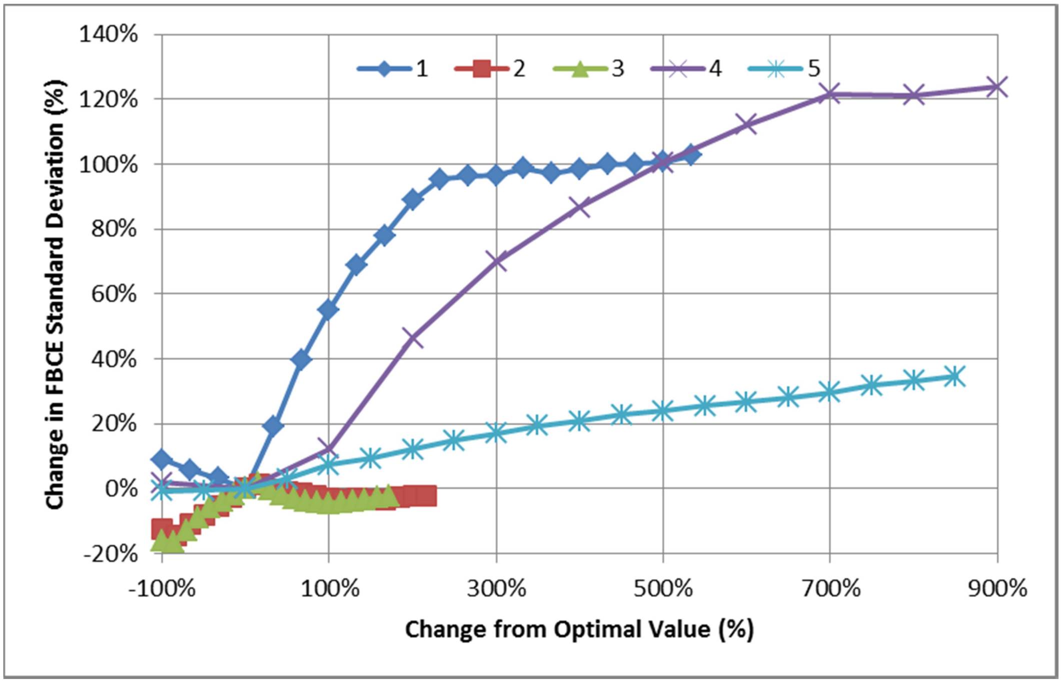

Figure 6.25: Percent Change to FBCE Standard Deviation for Future Groups

As shown, future group five, encompassing the most dangerous futures, is also the most resilient. Additionally, this analysis reveals that, compared to mean, all groups' standard deviation is relatively sensitive to the number of escorts. Furthermore, at as shown by this framework, optimizing decisions to minimize cost in some of the future groups, ones with high logistic burden with and without high end-user demand, almost maximizes risk. In closing, group five futures demonstrate another interesting trend. Intuitively, one might expect the most dangerous futures to have the highest ratio of escort assets. However, because they are modeled as generally high value assets, the consequences of escort exposure exceed their protective benefit and losses to logistic assets are simply accepted. This is not an agreeable contingency as, without changes to the modeled logistic structure, this would mean the loss of system operators. Further into the future, unmanned, completely autonomous vehicles, aircraft, and vessels may completely change the way the DoD thinks of energy and logistics and, accordingly, the assumptions of this framework. However, in the short-term, this seems like a great place for near-available, unmanned, semi-autonomous logistic systems and justification for further investment.

6.7 Conclusions, Policy Implications, and Future Work

In this work, we expanded on the complex conversation of energy in military, first addressing monetary concerns and then enlarging the focus to important considerations (e.g., technological development). We then demonstrated some of the energy, capability, and logistic implications of that discussion with a comparison between conventional and directed-energy weapons. Next, we introduced an expanded framework that incorporated a revised version of the equation from Chapter 2. This framework was specifically designed to create a tradespace to directly compare system capabilities and FBCE across a deeply uncertain security and technology environment. We then demonstrated the potential value of these changes to decision makers with several examples that included both historical and future planned weapon systems.

This method provides a systematic, quantitative means to put energy more on par with other decision factors during tradespace analysis when appropriate. It encourages appreciation of the uncertainty involved, chance of predictive failure, and maintains the ability to be tailored to the needs of the analysis and decision makers. This method tests acquisition choices over a range of possible futures. It can reveal choices that perform better and mitigate energy risk over a wider range, highlight the importance of present-day uncertainty and encourage flexible strategies that maintain options further into the future, and prepositions the DoD to more easily recognize pathways stressful to energy and capability given whatever choice is made. This last benefit would allow them to take action to limit the likelihood of a stressful future progressing or move to mitigate the consequences as it develops.

This framework may work well as a complement to more traditional DoD analysis tools. Energy is not a critical factor in every decision for every system in every potential contingency. However, as demonstrated in this and previous chapters, it can significantly impact operations either indirectly and directly. With the ability to be tailored to the necessary level of detail and highlight stressful pathways, this framework can help focus more costly, time-intensive analysis, where it is most beneficial.

Despite these advantages, this framework is not without limitations. Mapping effectiveness from capability through the JCAs and expert elicitation is an imperfect process. While creating a common language to discuss it, the JCAs are broad categories of capability. It is not a challenge to envision how two systems with overlapping JCAs actually have very different capabilities. For example, a short range drone and manned fighter aircraft may share the ability to ability to engage a soft surface target via kinetic means in certain futures but not all futures. Even in common futures, this capability is not identical. It is a function of such factors as loiter time, carrying capacity, munition details, time from basing location, and target specific details. In other words, capability itself is a multidimensional concept dependent on many uncertain terms. However, while reducing capability to a single distribution via the JCAs and expert elicitation is a simplification, it does not nullify the value of the framework. Several processes during acquisition already require the DoD to compare dissimilar capabilities to determine the arguably best overall choice. While broad, the JCAs create terms to compare relatively similar capabilities that should sufficiently serve the intention of this first-order framework.

While not the focus on this work, expert elicitation is not easy. Balancing the issues raised on page 170, it must be carefully and systematically planned and executed to reduce the chance of such issues as bias, error, framing, and overconfidence [98]. However, as mentioned before, the existence of data does not eliminate the value of expert opinion. Given the uncertainty involved and the need to plan contingencies for events that haven't happened in modern times or at all (e.g., major world war, organization wide cyber-attacks, and large-scale Pacific conflict with autonomous unmanned systems), any historic data is at best an indication of a subset set potential futures. Regardless of how the framework is filled, some amount of predictive failure needs to be maintained

Flexibility in the future space is critical to properly highlight the burdened energy and capability tradespace differences between compared systems without needlessly encumbering analysis. However, this adaptability also creates the hazard of selectively choosing futures to favor one choice over another. Whether the unintentional result of cognitive biases or the intentional outcome of an agent with personal motive, a narrow focus on a small subset of plausible futures can create the appearance of a preference that is merely an artifact of analysis. As with elicitation, this issue can be mitigated to some extend by carefully designing a process to guide FBCE space creation. That process would itself need to balance being overly restrictive or too uncontrolled. Inevitably, some part of the responsibility for judging the quality of FBCE will fall on the decision maker. Just as with benefit cost, cost-effectiveness, and other forms of economic analysis, normative analysis decisions and assumptions will have to be made. Decisions maker need to be made aware of at least the most important ones so they can reject the analysis if appropriate or at least understand the applicability of the tradespaces presented

The flexible future space and uncertainty in general presents challenges for any organization that must defend its decisions in a political environment. Preference for a FBCE or effectiveness distribution can be somewhat subjective. For example, depending on risk aversion, certain military decision makers may focus on options that reduce spread, mitigate risk, or spend more in the short-term to maintain flexibility later. Being able to defending such a decision in front of body that thinks in terms of annual budgets is not a given. Similarly, there is the issue of defending those futures considered versus those ignored.

Future work will design a detailed process to help scope the FBCE Space to make it more implementable in the DoD. Additionally, we plan to conduct expert elicitation trials to refine this process and create guidelines for further aid implementation, as well as conducting more detailed analysis on the potential impact of future technologies such as next-generation autonomous, unmanned. systems.

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Chapter 7: Dissertation Contributions

In this thesis, we examined energy's role in many aspects of military operations. The work presented is intended to inform better policies and investment decisions for military acquisitions. The discussion highlighted areas within the DoD's understanding of energy that are lacking or whose development has recently faltered. The new metric discussed may allow the DoD to better manage and plan for long-term energy-related costs and risk. It was broken into five chapters.

Chapter 2 grounded the conversation with some background information on logistics and energy demand in the DoD, implementation attempts and their limitations. It then introduced a new framework for FBCE and demonstrated its use. Through this framework, decision makers could focus on the key factors impacting energy demand and mitigate long term costs and risk for the organization. Providing a deeper exploration than offered in Chapter 2, Chapter 3 examined the Imperial Japanese Navy's operational decisions surrounding Guadalcanal in World War II to explore the important and inseparable connections between military capabilities and energy costs. This work simultaneously demonstrated the need to create and challenge of creating an energy metric that usefully balances simplicity, complexity, and flexibility. Chapter 4 traced the development of FBCE and the surrounding discussion in the DoD and Department of Navy. It highlighted how focused effort over the last fifteen years seemed to improve understanding and appreciation of energy but ultimately failed to find a way to translate that to decision makers before losing momentum. Chapter 5 demonstrated the value of the framework from Chapter 2 using the example from Chapter 3. Chapter 6 further expanded on the complex conversation of energy in military tradespace and offered additional adjustments to the framework specifically designed to deal with the issues of scoping a deeply uncertainly problem and creating a tradespace to directly compare system capabilities and FBCE. It then illustrated its use and value to decision-makers with nominal present-day systems and possible future technologies.

In the end it is evident that energy deserves a place in military decisions and tradespace analysis on parity with other decision factors. Though not easy to do right or critical in every decision, energy has been a decisive factor throughout history and there is plenty of evidence to suggest it will only become more vital in the future. Reversing recent trends, funding must be found to reinvigorate the discussion, support data collection (e.g., from real-world operations, red versus blue wargaming, and other exercises), and encourage a renewed development of decision and tradespace tools. This work presented a multitude of ideas and one such tool intended to highlight the need or lack of further more in-depth analysis. Besides financial encouragement, procedural support is essential. The array of agencies involved in the conversation and in charge of the various procedural documents need to consolidate terminology and focus intent (e.g., clarifying the difference between ESA and FBCE or eliminating one). One specific recommendation that impacts all these areas is revising next year's NDAA. In general several sections in the public law governing "Consideration of Fuel Logistics Support Requirements in Planning, Requirements Development, and Acquisition Processes" should be updated. For example, planning processes should not only consider the "requirements for, and vulnerability of, fuel logistics" but also how that vulnerability may impact non-logistic capability and the capability requirements development process needs to require not just a fuel efficiency

KPP but a burdened fuel KPP with some sort of sensitivity analysis. Currently, Section 332, paragraph and (g) provides that:

> “(g) Fully Burdened Cost of Fuel Defined.—In this section, the term 'fully burdened cost of fuel' means the commodity price for fuel plus the total cost of all personnel and assets required to move and, when necessary, protect the fuel from the point at which the fuel is received from the commercial supplier to the point of use” [1].

This should be changed to:

> (g) Fully Burdened Cost of Energy Defined.—In this section, the term ‘fully burdened cost of energy’ means the capitalized price for energy plus the total cost of all personnel and assets required to move and, when necessary, protect the fuel from the point at which the fuel is received from the commercial supplier to the point of use to include the possibility of personnel and asset loss. Due to scenario dependency and uncertainty, this cost shall be calculated in at least two fundamentally different futures and left in terms that denotes not just expected costs but the spread involved.

Updating the terminology used from FBCF to FBCE shows appreciation of improved understanding since the original enactment in 2009 and continuing interest in the concept. Improving the definition compels the incorporation of several critical aspects of FBCE highlighted in this work that are currently not required in analysis. Expanding its place in various processes (e.g., planning and acquisition) allows for more timely feedback on current processes to help guide improvement. For the DoD, the value to investment is two-fold. First, supporting the development of these decision tools reduces organizational risk and consequence of future energy demand and energy-related capability loss. Second, these same decision tools can also reveal the energy-related weaknesses of less prepared opponents, revealing otherwise hidden operational opportunities.

7.1 References

[1] U.S. Federal Government, 10 United States Code A - General Military Law Part IV Chapter 173 Section 2911. 2014.

Chapter 8: Appendices

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Appendix A: Fully Burdened Cost of Energy: Limitations and Value of Incentivizing Logistic Burden

Abstract

The Department of Defense (DoD) is the single largest purchaser of petroleum fuels in the nation and world [1]. This dependence creates a significant sensitivity to that market's price uncertainty and represents a substantial risk to the organization. A system-wide method to influence spending on petroleum and energy in general at the weapon-system acquisition decision point was created and is known today as Fully Burdened Cost of Energy (FBCE). Despite early interest, FBCE has been abandoned by all but a few offices across the DoD today.

This paper makes a contribution to the literature by addressing the following issues:

Analyze an existing method used to calculate FBCE and identify model limitations that have seemingly prevented it from influencing acquisition decisions as intended.

Construct a more robust FBCE method that addresses these limitations by modeling interactions between demand and logistic costs, the inherent uncertainty of forecasting and correlations between inputs, and demonstrate the value of such changes to an acquisition decision maker.

Several advantages and limitations were found by analyzing an existing method. Since it satisfies existing regulatory requirement, it establishes a baseline to build from and to compare other methods against. Limitations of the baseline method were categorized into the following groups: missing components (e.g., not accounting for lost escort losses), lack of uncertainty modeling (e.g., assuming fuel demand is constant and known), and lack of variable correlation (e.g., likelihood of attacks and convoy speed are not independent). In general, these limitations

suggest that the current implementation of FBCE prioritizes simplicity to such an extent that important insights are lost and the relevance of the metric is eliminated.

Deterministically incorporating the missing components significantly alters the average delivered fuel price. Because many distributions are not symmetric and many of the relationships between variables are non-linear, adding uncertainty to the model also significantly affects fuel price. The preliminary analysis on correlation highlighted the need for further analysis.

In its current form, the value of FBCE to an acquisition decision maker is highly dubious. It is incomparable to other costs at acquisition decision point and the importance of any calculated value relies on the decision maker's assumption of the modeled scenarios' significance. As a consequence unless it is changed, FBCE is likely to continue to be ignored. Simply increasing the amount by which fuel costs are burdened does not resolve these issues.

Future work will attempt to overcome these obstacles through more fundamental changes that allow direct inclusion of non-linear efficiency effects and non-monetary outlays as well as exploration of scenario and joint operation significance.

A.1 Introduction

A.1.1 Energy Usage

The Department of Defense (DoD) is the single largest purchaser of petroleum fuels in the nation and world [1]. As a percent of total US consumption, the quantity purchased has stayed relatively constant between 1.5% and 2.0% since Fiscal Year (FY) 1997 [2]–[16]. However, total spending has increased dramatically over the last decade. Figure A.1 shows inflation-adjusted annual spending on petroleum for FY 1997-2013. Spending costs, displayed by the bar chart and divided by service, were taken from the Defense Logistics Agency-Energy (DLA-E) Fact Books cited above.[27] Total purchase in billions of gallons is plotted at the top. As the figure illustrates, adjusted annual spending remains near recent highs despite the latest reductions in procurement to levels below FY2000.

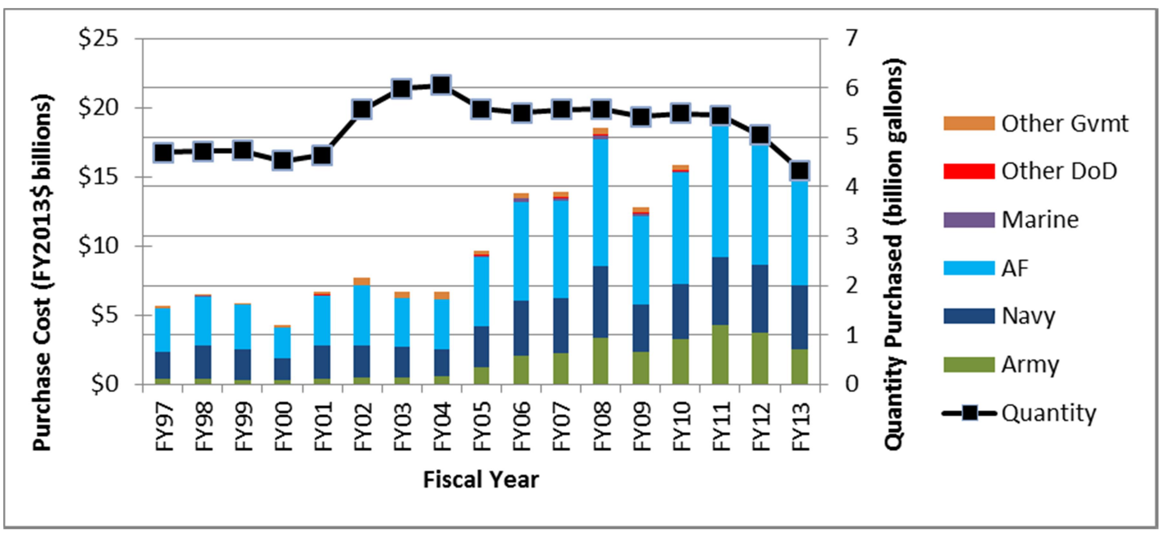

Figure A.1: DoD Annual Adjusted Cost and Quantity of Petroleum Products Purchased, Data from [2]–[16] and assembled by author

The crucial variable missing from the previous figure is commodity price. Figure A.2 maps adjusted annual DoD spending against the commodity price of jet fuel as reported by the

[27] The Defense Logistics Agency-Energy went by the Defense Energy Support Center (DESC) before 2010.

US Energy Information Administration (EIA) and DLA-E [17], [18]. The EIA data is monthly reported U.S. Gulf Coast spot price, while the DLA-E data is reported standard prices at intervals chosen by that organization. While the two prices are incorporating different costs and DLA-E reported jet fuel prices were available for a shorter window, they demonstrate similar trends and lead to the same conclusion; total DoD spending on petroleum products is highly sensitive to market prices outside of its control.[28]

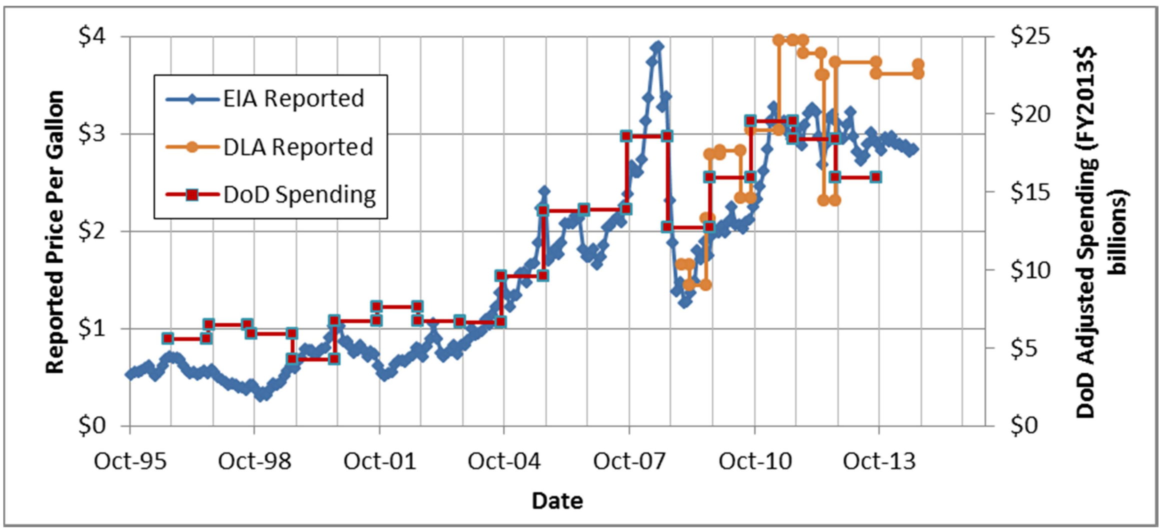

Figure A.2: Reported Commodity Price for Jet Fuel and DoD Adjusted Spending On Petroleum Products

Table A.1 shows fuel spending as a percent of total DoD outlays [19].[29]

Table A.1: DoD Fuel Spending as a Percent of Total Outlays

	Average	Standard Deviation
FY97-05	1.5%	0.25%
FY06-13	2.4%	0.33%

In summary, both the percent of outlays on fuel and the uncertainty in that quantity are growing in this timeframe.[30]

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[28] Despite the dramatic drop in the latter half of 2008, fuel prices have an overall upward trend for the examined timeframe. This paper does not assume that fuel prices will continue to increase in the future. Rather, the proposed arguments recognize the inherent uncertainty in fuel prices and the risk that represents to the DoD.

[29] These trends and others are shown graphically and discussed in more detail in the Appendix.

In the end, the DoD's dependence on petroleum-based fuels and sensitivity to that market's price uncertainty pair to create a significant risk to the organization. This suggests a lack of, and need for, some system-wide method to understand the policy relevance of petroleum spending subject to the uncontrollable cost of fuel.

A.1.2 Fully Burdened Cost of Energy

As stated, military operations create large fuel demands[31] that must not only be purchased but moved from the point of sale to its end-users. This final step requires a complex logistic web.[32] Not all logistics support fuel demand but a significant portion do. One report estimates that 70% of total Army logistic tonnage is fuel, while another found fuel to represent about 50% of average convoy load by volume [20], [21]. The monetary, non-monetary, and opportunity costs associated with this step may represent the most significant expenses associated with fuel demand.

In 2007, the DoD created a metric called the Fully Burdened Cost of Energy (FBCE) to value these hidden costs during the acquisition process more properly.[33] FBCE attempts to quantify all the major costs assumed by the DoD when satisfying the future energy demands of competing systems in their potential operational environment. These competing systems could be anything with a wartime use (e.g., combat ground vehicles, support aircraft or generators).

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[30] There has also been some analysis linking advances in modern warfare and technology to increased fossil fuel usage per soldier [20]. The highlights and limitations of this work are contained in the Appendix.
[31] In 2008, U.S. forces in Iraq consumed about 1.7 million gallons of fuel a day [30]. General Schwarzkopf's famous five-day flanking maneuver in Desert Storm consumed around 2.5 billion gallons of fuel [31].
[32] It is estimated that around one-half of all DoD personnel and one-third of the total budget are dedicated to logistics [1]
[33] Originally, this metric was known as Fully Burdened Cost of Fuel. Additional information on FBCE, a brief history and its location in the acquisition process can be found in Appendix B.

Figure A.3 summarizes the process to calculate FBCE. The left-hand side shows the general steps with the office of Operational Energy Plans and Programs' (OEPP's) recommendations shown in the center [22]. Fuel originates at the point of sale, where capitalized costs are already incorporated. These represent the per-gallon "base cost" of fuel. Then, the per-gallon costs of a scenario-dependent, demand-dependent, military-owned logistic chain are calculated and referred to as "additional logistic cost."[34] Summing these two costs determines the ADP ($/gallon). Finally, the FBCE is calculated by multiplying the daily system demand by the ADP.[35] Assuming point values for each input results in a deterministic calculation for ADP and FBCE; including uncertainties results in ADP and FBCE distributions. In application, significantly different methods of calculation exist as these details are not regulated.

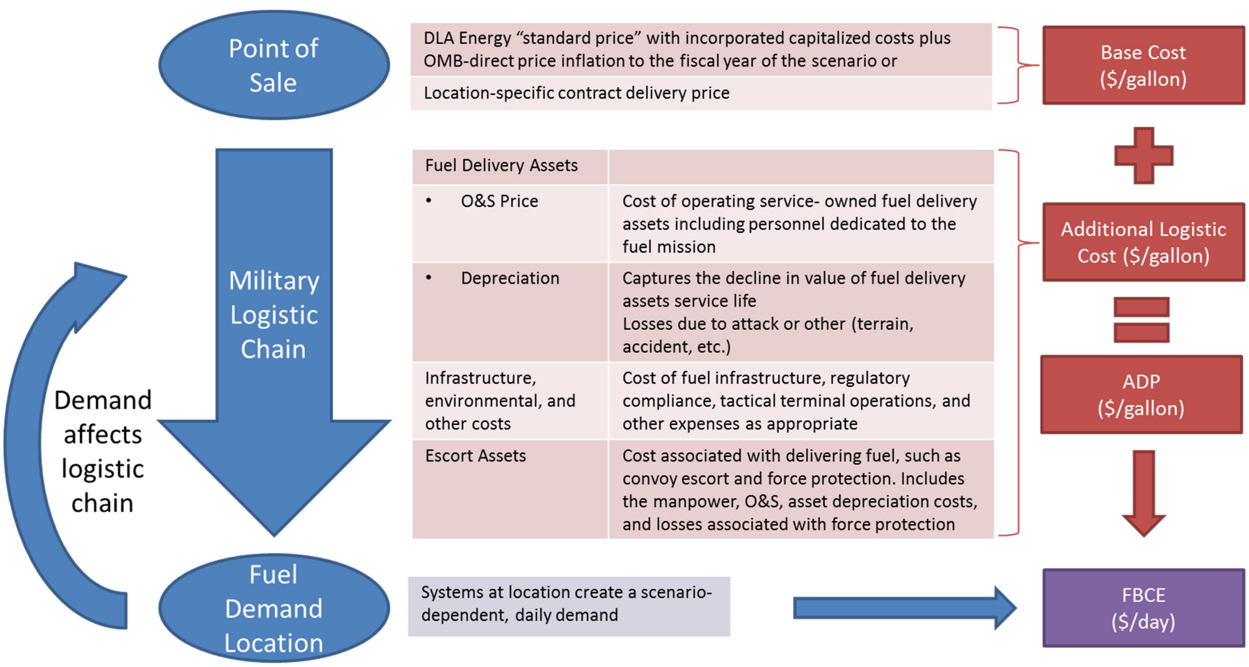

Figure A.3: FBCE Cost Elements and Calculation Framework

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[34] The scenario-dependent, demand-dependent logistic chains are discussed in more detail in the Appendix.
[35] While confusion in terminology exists in the DoD, the outlined delineation between ADP and FBCE follows guidance from OEPP [22]. In that guidance, ADP is an intermediate calculation measured in dollars per gallon that is used to determine FBCE, quantified as dollars per wartime scenario day for a system.

As mentioned, FBCE models future scenarios that represent operational environments but only in wartime. Peacetime demand is assumed at the point of sale. As a result, FBCE adds costs to only a portion of the spending illustrated in Figure A.1. Shown in Figure A.4, an estimate of this portion demonstrates that a large portion of fuel quantity increases from FY2001-13 are attributable to operations in relatively small, albeit geographically distant, operations.[36,37] Additionally, this portion of fuel use is much more sensitive to future uncertainties than peacetime use. All of which adds to the potential value of FBCE to the DoD.[38]

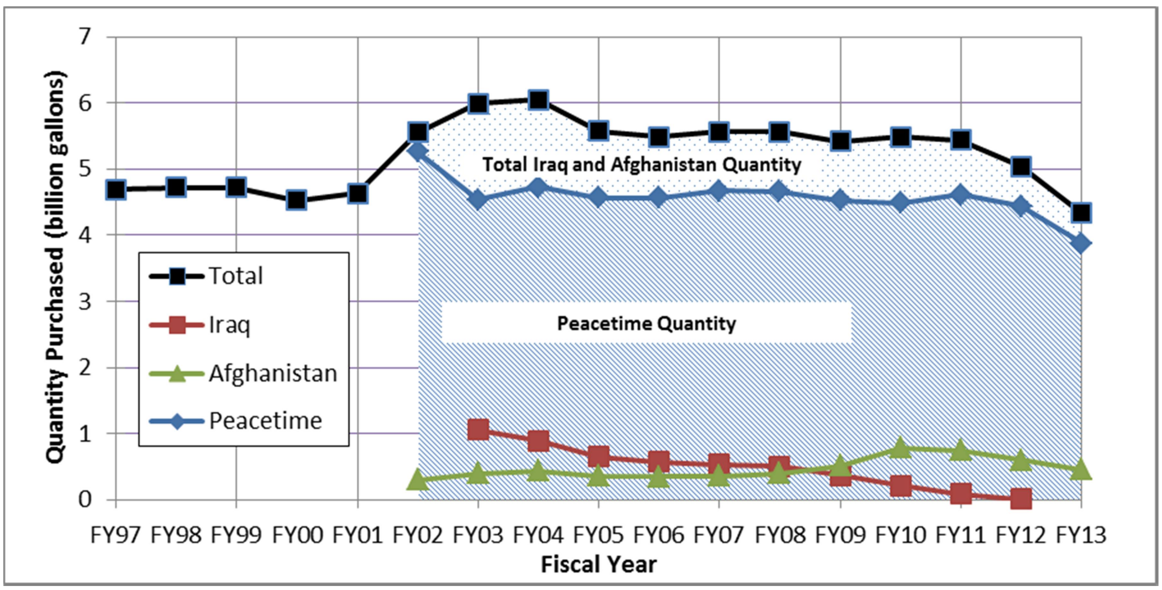

Figure A.4: Total, Iraq, Afghanistan and Peacetime Quantity of Petroleum Products Purchased

Originally, FBCE was embraced by several organizations across all services of the DoD. However, since 2012 support for FBCE has waned for all but the Army. A more detailed discussion of this transition is found in Appendix B: .

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[36] The details behind this calculation and discussion are located in Appendix B.
[37] General Schwarzkopf's previously mentioned five day maneuver used an estimated 30% of the 8-10 billion gallons of fuel consumed by the DoD in FY91.
[38] Indirectly, the data also shows higher fuel intensity per troop in theater. Over these years, fuel purchased in Iraq and Afghanistan averaged around 16% of total DoD purchase (range 5% to 24%). While on average, only around 10% of the total active duty force or 4% when including Reserve members and DoD civilians were located in theater [32]–[40]

FBCE's fall from favor seems to be the result of a basic disconnect between its designers and implementers. Given how it is currently calculated and where it is incorporated in to the existing acquisition process, there is no clear connection for how FBCE could ever be relevant to an acquisition decision maker.

A.1.3 Research Questions

In the end, there are two troubling trends working in concert today. First, the DoD spends a significantly larger amount on petroleum fuels relative to just a decade ago[39] and that spending is highly sensitive to uncontrollable and uncertain market prices. This represents risk and vulnerability to the organization that could grow and ultimately undermine the effectiveness of the very force it supports. Second, the metric designed to value the total costs of fuel during the acquisition process and help alleviate the first issue has seemingly been abandoned. Acquisition decisions being made today do not have a formal metric to evaluate future fuel demands.

This paper makes a contribution to the literature by addressing the following issues:

Analyze an existing method used to calculate FBCE and identify model limitations that have seemingly prevented it from influencing acquisition decisions as intended.

Construct a more robust FBCE method that addresses these limitations by modeling interactions between demand and logistic costs, the inherent uncertainty of forecasting and correlations between inputs, and demonstrate the value of such changes to an acquisition decision maker.

[39] The previously displayed analysis on fuel purchases, expanded in the Appendix, also indicate another disturbing trend. While the quantity of fuel purchased by the DoD is at or near all-time lows dating back to the Vietnam War, both the amount and percent of the DoD budget spent on that fuel remains near recent all-time highs.

The rest of the paper is organized as follows. Section 2 extends the previous theoretical conversation of FBCE to application. By assuming two competing systems, a baseline FBCE can be calculated, which highlights the value and limitations of current modeling. Section 3 establishes methods to expand the baseline framework and address some of the identified limitations. The results of this expanded framework are shown in Section 4. Given its current application and limitations and the regulatory structure that it exists in, Section 5 concludes the analysis, identifies policy implications and identifies areas of future work.

A.2 Analysis of FBCE Existing Method

This section extends the introduction behind FBCE to application. This detailed exploration highlights the value and limitations of current methods.

A.2.1 FBCE Method Demonstration

To model current FBCE methods, a single wartime scenario and deterministic model are developed based on regulatory and operational guidance [23], [24]. These in turn are used to generate a scenario-dependent, point estimate for ADP. Finally, a scenario-dependent fuel demand is assumed and combined with the calculated ADP to compare the FBCE of two potentially competitive systems. For this example, the competing systems are assumed to be load-dependent generators, which consume fuel to meet the electrical load of a forward-deployed location within the established scenario.

Overall, this model accounts for the operations and support and depreciation costs of fuel-delivery, fuel-delivery support and escort assets normalized to a 60-truck fuel convoy with a capacity of about 350,000 gallons per delivery.[40] All other potential costs mentioned in Figure A.3 are ignored. Additionally, current models ignore the feedback loop shown in that figure, meaning ADP and risks are independent of the fuel demand.

[40] A detailed description of this process is located in the Appendix.

Table A.2: Parameter Value for Notional Scenario

Parameter	Value	Units	Description
From Yearly to Daily Peacetime Costs			
Training Days Per Year	242	Days	Number of Training Days in Peacetime
From Daily Peacetime to Scenario Costs			
Equipment Factor	2	Unitless	Wartime use cost relative to peacetime
Personnel Factor	10%	Percent	Wartime personnel cost relative to peacetime
From Daily to Per Gallon Scenario Costs			
Days to Deliver	2	Days	Round trip delivery time
Availability Factor	100%	Percent	Percent of 60 fuel trucks available to support particular delivery
Losses Due to Enemy	5%	Percent	Percent of fuel trucks lost to enemy action during delivery
Mechanical Failure	5%	Percent	Percent of fuel trucks lost to mechanical failure during delivery
Standard Price of Fuel	$4	2012$ per gallon	DLA-E published price of fuel which includes capital cost of delivery to point of sale
Average Service Life - Aerial	20	Years	Average life of aerial assets
Average Service Life - Ground	10	Years	Average life of ground assets

Using the inputs assumed from available guidance and listed in Table A.2, the model determines a baseline, point-estimate ADP of $9.75/gallon, a 240% increase over the standard fuel cost.

Converting this to FBCE requires the assumption of two competing systems and the calculation of their daily fuel demand per scenario day. This paper demonstrates this with a comparison between two alternatives of load-dependent generators using publically available specifications. The first alternative consists of two 500 kW generators modeled after a Caterpillar (CAT) Prime 500 kW diesel generator [25]. The second alternative contains one 1000 kW generator modeled after a CAT Prime 1000 kW diesel generator [26]. As it is outside the focus of this initial work, other differences (e.g., total capital investment, the value/cost of redundancy) are ignored.

Even in a single wartime scenario with a deterministic ADP, the fuel demand of these generators depends on uncertain electrical load. However, current FBCE application ignores this.

For this example, a constant demand of 550 kW per hour is assumed. Table A.3 shows the fuel demand, base cost and FBCE for the two competing systems at this load.[41]

Table A.3: Fuel Demand, Base Cost and FBCE for Load of 550 kW per hour

System	Fuel Per Day (Gallons)	Unburdened Cost (Base = $4/gallon)	FBCE (ADP = $9.75/gallon)
2x500 kW	1,020	$4,080	$9,940
1x1000 kW	1,035	$4,140	$10,090
% Difference in Systems	1.5%	1.5%	1.5%

For the assumed load, the 2x500 kW alternative is slightly preferred in all categories (i.e., a lower fuel demand and a lower cost to meet that demand at both prices.) Critically, because the same ADP is used for both systems, the percent difference between FBCE and unburdened cost is the same 240%. Accordingly, this enlarges the difference between systems from $60 to $145, which increases the cost of fuel demand but never affects the percentage difference.

Whether or not this change is enough to make FBCE relevant to an acquisition decision maker is uncertain. For the purposes of this analysis, FBCE is relevant if the $145 difference affects the decision made when the $60 difference did not.[42]

Related to relevance, the per-scenario day costs of FBCE are impossible to directly compare to other costs, such as capital investment, seen by an acquisition decision maker. A more direct comparison is possible but violates the intent of the metric [27]. Additionally, it requires the assumption that the short-duration, single scenario modeled accurately represents the

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[41] For the 2x500 kW alternative, one 500 kW generator is supplying 500 kW while the other supplies 50 kW.
[42] This simple example is for demonstration purposes only. Actual systems could have values many orders of magnitude greater.

system's future energy costs across its entire life.[43] Given the potential variations in system cost across a range of uncertain operational scenarios, this is highly unlikely and would result in a misleading calculation. For example, FBCE preference changes to the 1000 kW generator if a 900 kW scenario load is assumed.[44]

A.2.2 Value of Model

As implemented, this current method establishes a framework to build on, and compare to, in further work. It also establishes a lower-bound estimate potentially useful to the decision maker and lastly, satisfies the regulatory requirement to calculate FBCE.[45]

A.2.3 Limitations of the Baseline Model

From its description, there are several evident limitations that may contribute to this lack of decision-maker relevance. This report addresses these limitations in the following groups: missing components, lack of uncertainty and lack of variable correlation. In general, these limitations suggest that the current implementation of FBCE prioritizes simplicity to such an extent that important insights are lost and the relevance of the metric is eliminated.

The analyzed method fails to account for several potential important costs of fuel delivery. First, the method does not account for the possibility of escort losses to such events as mechanical failure or enemy action. Second, the method only accounts for monetary costs.

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[43] It at least requires the assumption that peacetime and other possible scenario energy costs are small enough relative to the modeled scenario costs to ignore.
[44] At this load, the 1000 kW generator's FBCE is $740, or 4.8%, less than the two 500 kW generators'.
[45] A 2008 report by the Army Environmental Policy Institute estimated FBCE for a Stryker brigade in Iraq between $14 and $17 per gallon [28].In 2010, the Marine Corps estimated FBCE in Afghanistan between $9 and $16 per gallon for ground delivery and $29 and $31 per gallon for air. An Army study estimated FBCE in Iraq at $9 to $45 per gallon, depending on the type of force protection used and the delivery distance. An Air Force study estimated it at $3 to $5 per gallon for ground and $35 to $40 per gallon for air. The often cited $400 per gallon represented the FBCE of a very specific, multi-stage helicopter fuel resupply [41].

Incorporating some externalities, such as greenhouse gas emissions, may be important to understanding the true cost petroleum fuel reliance [21], [28]. Most importantly, this fails to account, either monetarily or through some normative decision process, for the value of the human resources invested in delivering fuel[46]. Third, the method assumes ADP and risk are independent of fuel demand, ignoring the non-linear interaction between logistic burden and end-user fuel demand.

Next, the model is completely deterministic. It calculates a single FBCE from the combination of an assumed known fuel demand and ADP calculated from a deterministic scenario. This ignores all the inherent uncertainty involved in each of the steps necessary to calculate FBCE. Among other consequences, this results in an inflexible notional scenario that exacerbates the issue of FBCE relevance. Without some scenario breadth, there is no way for decision makers to understand the significance of calculated FBCE differences even if they are numerically large. Of course, adding uncertainties complicates the comparison, but this additional difficulty is necessary to have a robust and relevant approach.

Finally, as a result of deterministic inputs, the method is unable to model any correlation between parameters. For example, having longer delivery routes should increase the rate of mechanical failure and allocating escort assets to fuel delivery should decrease the rate of enemy interdiction.

[46] Work supporting this missing component is located in Appendix B.

A.3 Expanding FBCE Methods

An expanded FBCE model is developed by adding the identified missing components, incorporating uncertainty, and integrating correlations between input variables. This section discusses the value of, and establishes the framework for, such changes.

A.3.1 Escort Asset Loss

As previously indicated, the baseline model does not account for the possibility of escort-asset loss. These escort assets represent high-value systems. The loss of which, even if it were to occur very rarely, might significantly alter the cost of delivering fuel. Additionally, using them to protect fuel convoys represents an opportunity cost as they become unavailable for other missions.

The significance of including this low-probability, high-consequence event is determined by parametrically analyzing different escort asset loss probabilities. When lost, the total cost of that asset minus all support costs is attributed to the fuel delivery.[47]

A.3.2 Non-Linear Interaction between ADP and Demand

Accounting for escort and personnel losses increases the ADP calculation but affects system comparison proportionally. However, in many scenarios, ADP is also demand-dependent. Accordingly, changing end-user fuel demand should have non-linear effects to fuel delivery costs (e.g., step functions for new equipment and assumption of more risk to satisfy increasing

[47] The costs accounted in this method are from FORCES data that represent fleet-wide average equipment, personnel, support and acquisition costs as previously described. There is no attempt in this initial work to more accurately account for the value of the lost asset, which may significantly differ from the average. Additionally, while mentioned, there is no attempt to quantify scenario-dependent opportunity costs.

demand).[48] Accordingly, total fuel demand should influence both the magnitude of fuel required and the per gallon price.

These relationships are not directly implementable in the baseline model and require constructing demand dependence. One such scenario assumes that end-user fuel demand is proportional to the frequency of fuel convoys.[49] Reducing demand may allow fuel delivery assets to resupply other locations and escorts to conduct other missions. This decreases the portion of total costs for these assets that should be contributed to meeting the fuel demand for this location. The reduction in demand might also allow the fuel delivery assets to undergo more preventative maintenance, increasing the availability factor and/or reducing the probability of mechanical failure. Therefore, the more fuel efficient system is represented in a scenario with an appropriately lower ADP.

A.3.3 Uncertainty

Given the nature of calculating FBCE, incorporating uncertainty is critical in establishing FBCE relevance. Model runs based on average values can be very misleading. No one single deterministic scenario will ever actually happen. Accordingly, military planners need to consider the entire distribution of FBCE. Incorporating uncertainty allows decision makers to understand the significance of relatively rare events and think through contingencies.

This section establishes a framework to incorporate uncertainty to the current model first to ADP, then to demand, and finally to the connection between the two.

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[48] This is discussed in more detail in Appendix B.
[49] In practice, there are other options. An increasing or decreasing end-user fuel demand could be satisfied by proportionally altering the fuel convoy's size, frequency, or some combination of the two.

A.3.3.1 Uncertainty in ADP

Given the inherent uncertainty of the modeled scenario, distributions are incorporated into the parameters listed in Table A.2. This helps create a truer representation of the range of ADPs that could be encountered. For example, while a "normal" fuel delivery to the modeled location might take two days, issues related to weather, enemy action or mechanical failure could significantly increase this for any particular delivery. Additionally, if "normal" refers to average or median delivery time, then some convoys have to make the trip in less. Similar reasoning can be extended to understand the rationale behind adding uncertainty to the other parameters.

Uncertainty is also incorporated into the quantity and allocation of asset costs in the scenario's logistic chain. Again, the values used in the current method are assumed to represent the "desired" or average logistic chain for this scenario. As such, there must be some variability in the logistic chain for any a particular delivery. Additionally, various parts of the logistic chain range from important to critical. For example, a mission planner may assume the additional risk of resupply if no escort assets are available, depending on base risk and the need of the demand location. However, the unavailability of critical assets that eliminate the possibility of delivering any fuel would make the assumption of even small risk nonsensical. Combined with the previous discussion of how current application normalizes them, incorporating uncertainty into this part of the model requires breaking the analysis of scenario assets into the following three groups: escort assets, fuel delivery support assets and fuel delivery assets.

For escort assets (e.g., aerial scouts), distributions are assigned to the quantity of escort assets attached to fuel convoys and their allocation of total costs parametrically analyzed. [50]The relationship between the scenario and fuel delivery support assets (e.g., fuel terminal and personnel) is simpler than the first. Sensitivity to their allocation of cost is analyzed parametrically. For the last group, fuel trucks, the total cost of operation is allocated to the fuel user that requires its operation.[51]

A.3.3.2 Uncertainty in the Demand

As explained throughout this report, many of the steps of FBCE depend on the uncertain end-user fuel demand. For the generator example in Section 2, fuel demand is a function of the uncertain electrical load where they are stationed. The assumption of a deterministic load in the current method only presents the decision maker with a point estimate of the actual distribution of FBCE, exacerbating the relevance issue.

This report demonstrates the value of incorporating uncertainty in the demand by extending the previous comparison between the two generator alternatives. Their fuel demand is linked to an uncertain electrical load and the affect to FBCE is calculated.

A.3.3.3 Uncertainty in ADP and Demand Interaction

The connection between ADP and demand is related to the non-linear interaction between logistic burden and demand. Changing demand has an effect on the logistic burden associated with satisfying that demand and, accordingly, has an effect on ADP. For example, a greater

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[50] The information on how and why uncertainty is incorporated for these groups is located in the Appendix.
[51] In reality, fuel trucks can be used to service multiple operations at the same or different locations. For this initial work, this possibility is ignored and the normalized fuel convoy is sent as often as needed to satisfy the fuel demand of a single end-user at a single location.

demand for fuel implies more frequent and more predictable fuel convoys (i.e., risk and ADP increase with demand).

This report explores the potential significance of this interaction by expanding the generator example, where it is assumed that larger loads increase demand and reliance on fuel. As demand increases so does ADP and its uncertainty as escalating risk must be assumed. Data is not available to calculate the exact relationship between demand, ADP and risk so several are assumed and the resulting significance analyzed.

A.3.4 Correlation

As defined in current application, model parameters are related. For example, attaching escorts to fuel delivery should have some effect on losses to enemies otherwise they would not be attached. When uncertainty is added to the model, these relationships need to be accounted for with correlations. This work did not find enough data to calculate the correlations between input variables. However, logic determines the direction and approximate size of the correlations. The significance of the assumed correlations can be evaluated parametrically. Once identified, sensitive correlations can be refined through enhanced modeling and expert elicitation.[52]

To demonstrate this addition of correlated variables, two interactions are modeled: the negative correlation between escort assets and losses to fuel convoys from enemy action, and the positive correlation between days to deliver the fuel and the rate of fuel convoy mechanical failure (i.e., having more escort assets assigned to support a fuel delivery decreases the probability of losing a fuel truck to enemy interdiction and longer delivery times increases the chance of fuel truck mechanical failure).

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[52] This report includes preliminary results. The parametric analysis of correlation estimates is planned to help determine the important relationships. Ultimately, expert elicitation may be required.

A.4 Results

All of the following work originates with the current model described in Section 2. Accordingly, the first three subsections add missing components to that deterministic model using stated assumptions and generate deterministic results. The next two subsections incorporate uncertainty and correlations. For space considerations, effects of intermediate steps on FBCE are not shown.

A.4.1 Escort Asset Loss

The current model has three types of escort assets. With the assumption of "high risk," two ground forces units, one aerial scout and one attack helicopter are assigned to the fuel-delivery route. The effect on ADP for a single delivery is shown in Table A.4.

Table A.4: Escort Loss Significance on ADP

	ADP ($/gallon)
Current Model	$9.75
Amortized Loss	
1 Ground Forces Unit	$160.00
2 Ground Forces Units	$320.00
1 Aerial Scout	$820.00
1 Attack Helicopter	$2,100.00
All	$3,200.00

As indicated, the loss of an escort is very significant to the cost per gallon on the delivery in which it occurs. The influence on the average ADP is analyzed across various probabilities of escort loss and shown in Table A.5. For this initial analysis, it is assumed all loss events above are equally likely. For example, a 2% probability means there is a 2% chance of losing one or more escort assets or a 90% chance no losses will occur on the fuel delivery.

Table A.5: Escort Loss Significance on Average ADP

Probability of Loss	ADP
2%	$141.00
1%	$75.60
0.10%	$16.30

0.01%	$10.40
0.001%	$9.80

As shown, even at low probabilities of occurrence, escort loss has a noticeable influence on average ADP.

A.4.2 Non-Linear Interaction between ADP and Demand

For the deterministic current model, the relationship between logistic burden and fuel demand is demonstrated by assuming that daily demand is linearly proportional to ADP. Therefore, systems with higher fuel demands also cost more per gallon because greater costs and risk must be assumed to meet the greater demand. For the generator example, there is a 1.5% difference between options at the assumed load of 550 kW. Assuming an escort loss probability of 0.1%, Table A.6 illustrates the effect to FBCE.

Table A.6: Non-Linear FBCE Difference at 550 kW Load

System	Demand (gallons/day)	ADP ($/gallon)	FBCE ($/day)
2x500 kW	1,020	$13.40	$13,700
1x1000 kW	1,030	$13.60	$14,100
% Difference	1.5%	1.5%	2.9%

Importantly, there is not only a larger difference between FBCE, partially caused by the larger ADP from incorporating escort losses, but also the difference is not simply proportional to ADP.[53]

A.4.3 Uncertainty

The following subsection incorporates uncertainty in the three stages outlined in Section 3. Results are generated through Monte Carlo runs, use a common random seed so direct

[53] The same assumptions lead to a similar change in expected casualty rates. The 2x500 kW alternative's demand results in an expected casualty every 32.3 deliveries while the 1x1000 kW's demand results in one every 31.3.

comparisons can be made, and consist of 1,000 iterations. Results are shown as probability density functions (PDFs) or cumulative distribution functions (CDFs).

A.4.3.1 Uncertainty in ADP

Uncertainty is first added to the scenario parameters used to calculate ADP. The range and shape of each distribution for this problem are based on available data; though the supporting data varies considerably across parameters. For example, a reasonable distribution of the increased personnel costs encountered in wartime, known in the model as personnel factor, is determinable from publicly available military information.

Table A.7 shows a summary of the calculation. [54] As demonstrated, the range in personnel cost increase is large and even the minimum calculated increase is greater than the 10% assumed in the baseline.

Table A.7: Summary of Increase in Personnel Costs

Weighted Average (Per Month)	Value (FY2012$)	Increase (FY2012$)	Personnel Factor
Peacetime	$4,800	-	
Minimum Wartime	$5,500	$760	16%
Most Likely Wartime	$5,600	$830	17%
Maximum Wartime	$8,500	$3,800	79%

The methods, rationale and assumptions incorporated in establishing reasonable bounds for the others distributions can also be found in the Appendix. A synopsis of the distributions incorporated into the baseline model and their related parameters are illustrated in Table A.8.

Table A.8: Distributions Incorporated in Baseline Model

Parameter	Distribution	Minimum	Maximum	Mean	Mode
Days to Deliver	Triangle	1	6	3	2
Equipment Factor	Triangle	0.9	4	2.3	2
Personnel Factor	Triangle	10%	80%	36.7%	20%

[54] The details of the calculation and assumptions are found in Appendix B.

Availability Factor	Triangle	60%	100%	85%	95%
Losses Due to Enemy	Triangle	0%	10%	4.7%	4.2%
Mechanical Failure	Triangle	0%	10%	5%	5%
Escort Ground Forces Quantity	Discrete Uniform	1	3	2	N/A
Escort Aerial Scout Quantity	Discrete Uniform	0	2	1	N/A
Escort Helicopter Quantity	Discrete Uniform	0	2	1	N/A

Assuming a probability of escort loss of 0.5%, Figure A.5 shows the ADP distribution for the current baseline model with and without uncertainty.

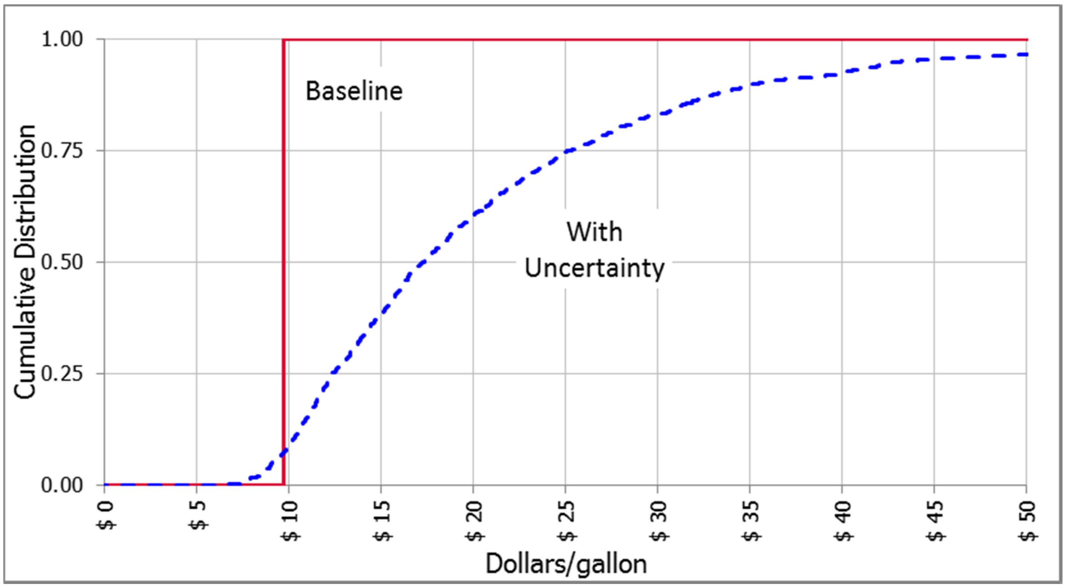

Figure A.5: ADP for Baseline and Model With Uncertainty

As displayed, it significantly increases ADP with the crossover occurring around the 8th percentile. Additionally, the effect of incorporating escort asset loss, assumed at 0.5%, on the distribution may be important for a decision maker to consider. Escort asset losses elongate the upper tail, significantly increasing upper percentile and mean ADP. This further highlights the limits of relying on mean ADP values and adds credence to the adoption of a robust strategy that places a value on the uncertainty of future fuel costs above the median forecast.[55]

A.4.3.2 Uncertainty in the Demand

[55] The comparison between generator system options is unaffected by this step. At this point in the analysis, they are both satisfying their fuel demand at the same uncertain ADP

As mentioned fuel demand is uncertain and, in the generator example, a function of uncertain electrical load. Figure A.6 shows the fuel consumption for the two generator alternatives as a function of hourly load.[56] As displayed, the 1000 kW generator is more efficient for loads to the left of the first dashed line, below around 40 kW, and to the right of the second, above around 570 kW. The 2x500 kW generators are more efficient for in-between loads. In general, the 1000 kW generator is dominant when efficiency of scale is more important, while the 500 kW generators are dominant when the non-linear fuel consumption at low load factors penalizes the larger generator significantly more than the two smaller ones.[57]

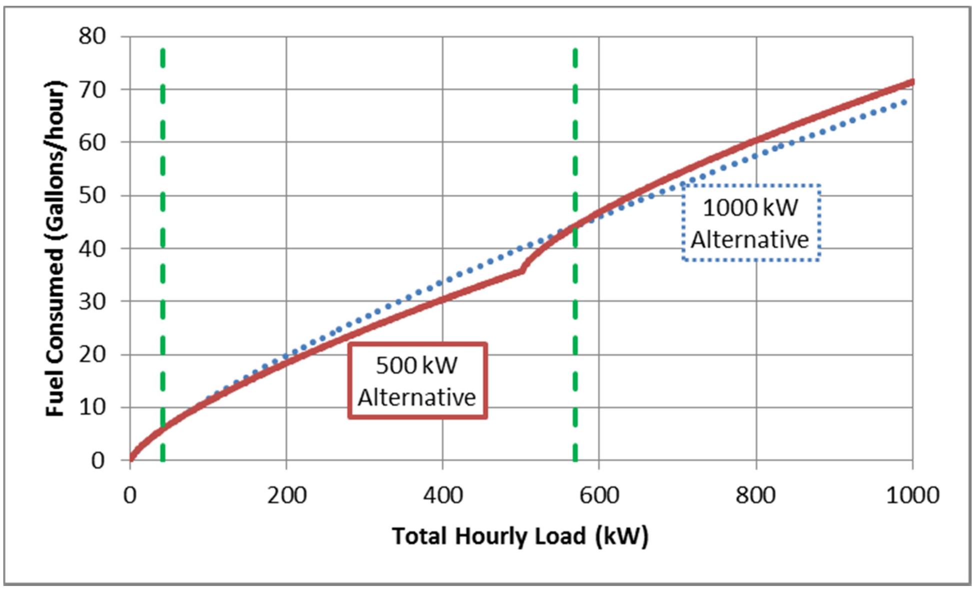

Figure A.6: Generator Fuel Consumption vs Load

As electrical supply systems have to be sized to peak rather than average loads, a load curve is assumed from a stateside utility that services the Northeast [29]. This load curve is scaled across peak loads ranging from 2 to 1,000 kW. Then, the per-day fuel demand for each of

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[56] A separate analysis for a similarly sized engine was used to extrapolate fuel consumption for lower load factors, as the manufacturer only published fuel-consumption data down to a 50% load factor [42]. Hourly loads above 500 kW per hour are satisfied through the most fuel efficient use of the two 500 kW generators.

[57] If all hourly loads between 0 and 1,000 kW are equally likely, the 1000 kW generator is more preferred.

these load curves is calculated for each generator alternative.[58] Finally, this load-dependent fuel demand is multiplied by the probability of requiring that peak load and the calculated ADP. For demonstration, this report assumes the probability of various peak loads is defined by the profiles displayed in Figure A.7. Both are normal distributions. However, Profile A has a larger uncertainty but lower mean compared to B. The details behind these steps and their effect on the comparison between the generator alternatives' FBCE is shown in the Appendix.[59]

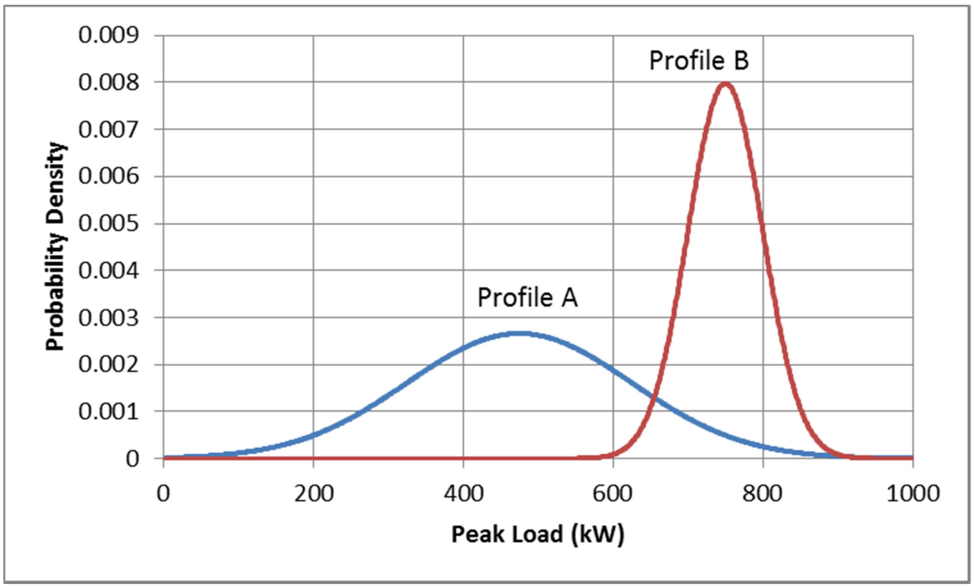

Figure A.7: Probability of Peak Load Profiles

A.4.3.3 Uncertainty in ADP and Demand Interaction

Up to this point, uncertainty has been added to ADP and demand but the same uncertain ADP is used over the range of uncertain demand. As previously discussed there is reason to believe that the amount of uncertainty between ADP and demand are related. This report assumes they are related through risk, where larger peak loads create larger demands, which tend

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[58] The 2x500 kW alternative's range of preference extends from around 50 to 710 kW. Accordingly, if all peak loads between 2 and 1,000 kW are equally likely, the 2x500 kW generators are preferred.

[59] In general, the 500 kW alternative is preferred for Profile A and the 1000 kW alternative for Profile B. However, the magnitude of preference and regret differs between the peak load profiles.

to increase the risk assumed in satisfying the demand and the corresponding distribution in ADP. Three functional relationships are assumed and shown in Figure A.8

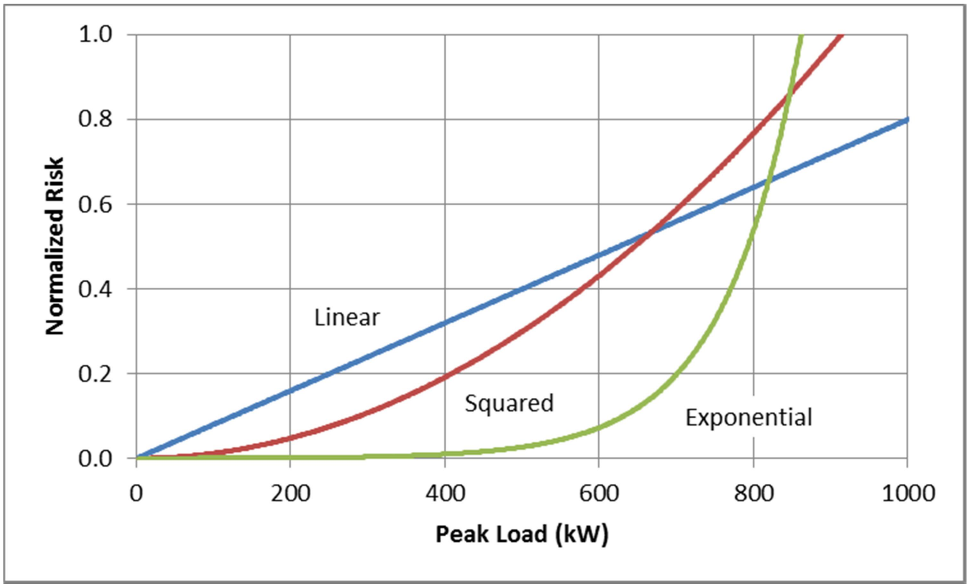

Figure A.8: Normalized Risk vs. Peak Load

For space considerations, only the exponential relationship is shown below. The others are included in the Appendix. As shown in Figure A.9Figure A.9:, ADP's distribution and the range of that distribution grows dramatically at higher peak loads.

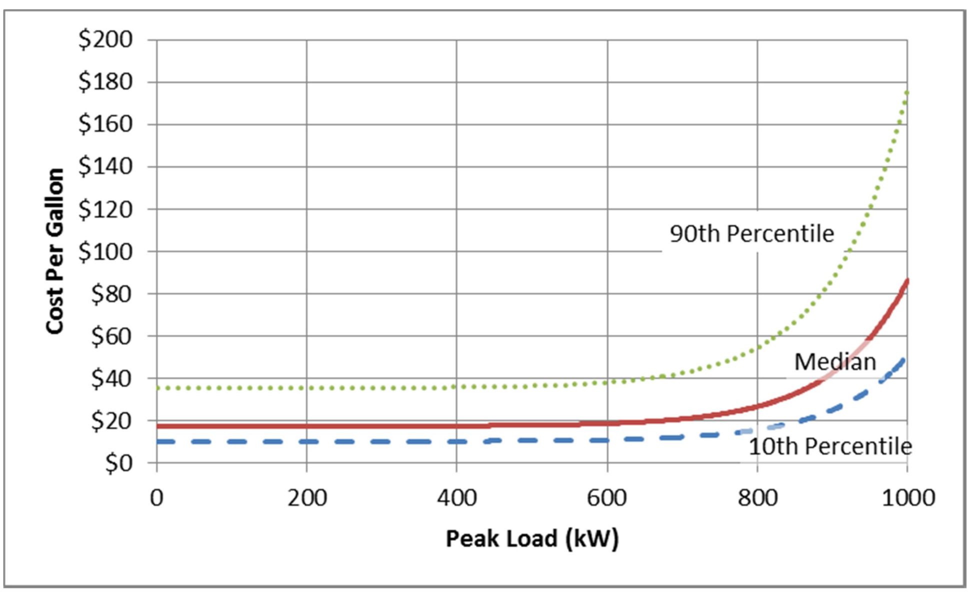

Figure A.9: Exponential Risk-Dependent ADP vs Peak Load

As before, the per-day fuel demand for each peak load curve is calculated for each generator alternative and then multiplied by the probability of requiring that peak load and the risk-dependent ADP. Figure A.10 and Figure A.11 show the resulting cost and cost difference PDFs respectively. The area under first represents FBCE, while the area under second represents FBCE difference. In Figure A.11, a negative cost difference indicates preference for the 500 kW alternative, while a positive cost difference indicates preference for the 1000 kW one. The shaded area on both shows the range between the 10th and 90th percentiles.

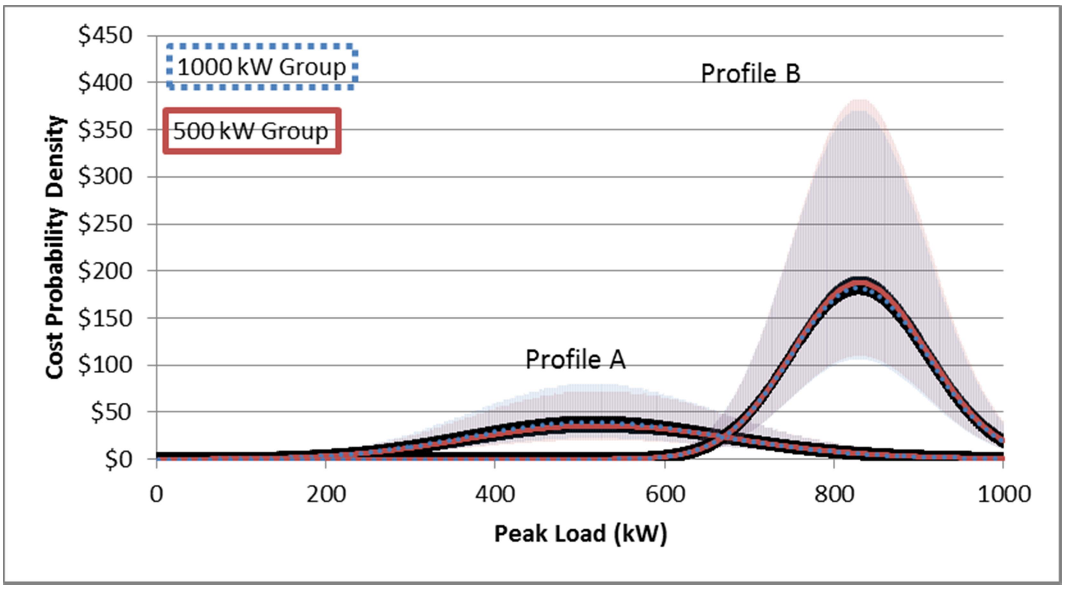

Figure A.10: Cost Probability Density Function vs Peak Load

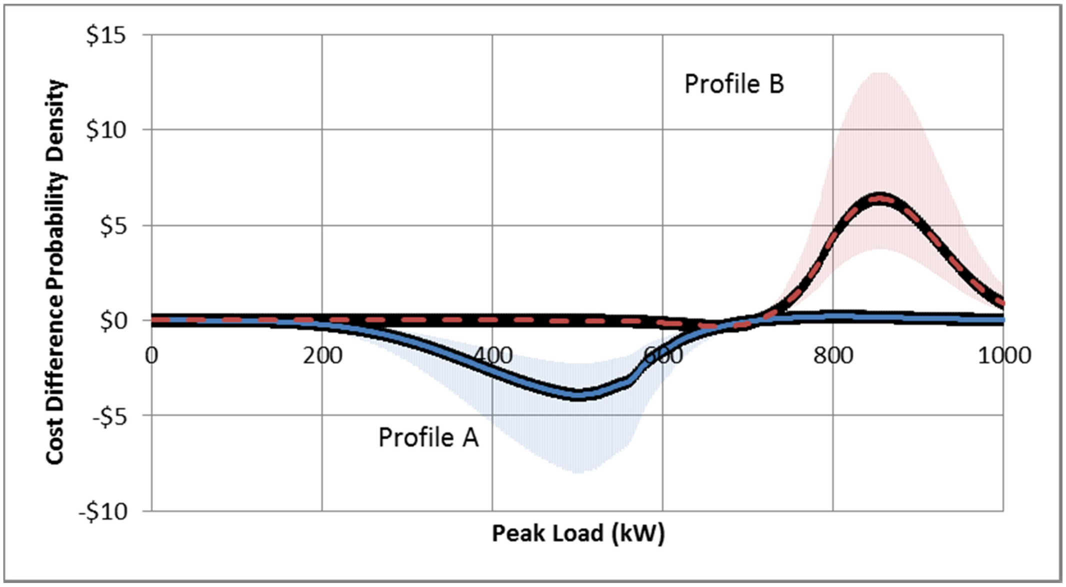

Figure A.11: Cost Difference Probability Density vs Peak Load

As the figures show, the 500 kW alternative is still preferred for Profile A and the 1000 kW for Profile B. However, the exponential risk relationship has both increased the magnitude of regret and decreased the magnitude of preference in Profile A relative to Profile B. As a consequence, the 500 kW and 1000 kW alternatives' FBCE difference are approximately equal across both profiles at the 10th percentile, while the 1000 kW option displays significant preference at the 90th percentile.

A.4.4 Correlation

Figure A.12 displays the CDF for the baseline with and without the assumed uncertainty and correlations. All correlations are assumed at either 1 or -1 to test sensitivity. As shown, the assumed correlations significantly affect the distribution of ADP.

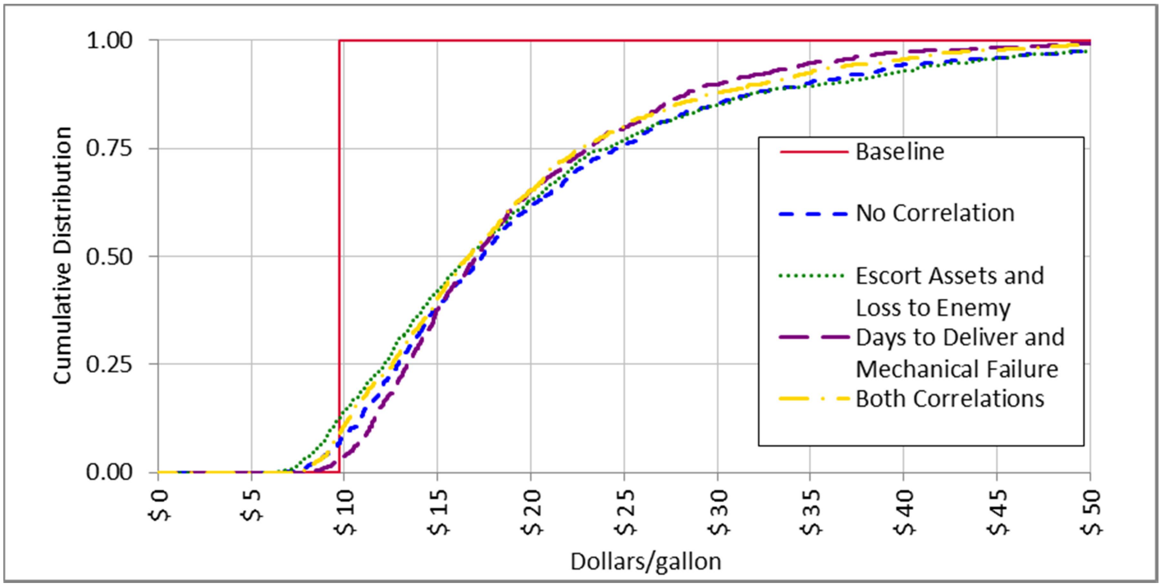

Figure A.12: Effect of Correlation on ADP Distribution

The negative correlation between escort asset quantity and loss to enemy action significantly reduces ADP up to the median value at which point it approximately follows the "No Correlation" distribution. The positive correlation between days to deliver and mechanical failure rate significantly increases ADP up to around the 40th percentile at which point it results in noticeably lower ADPs. Incorporating both correlations results in an ADP distribution that is stochastically dominant to the "No Correlation" distribution. The advantageous difference increases at higher percentiles.

A.5 Conclusions, Policy Implications, and Future Work

An analysis of current FBCE methods identified limitations in the following three areas: missing components, lack of uncertainty, and lack of variable correlation. Incorporating escort asset loss dramatically altered the average ADP depending on the assumed probability of loss. For example, a 0.1% escort loss rate assumption increased the average ADP by around 37% from $9.75 to $13.40. Accounting for the connection between logistic burden and fuel demand increased a 1.5% fuel demand difference to a 2.9% FBCE difference in the developed example.

Adding uncertainty to the model increased the median ADP by around 78% from $9.75 to $17.40 and highlighted important characteristics in the distribution's tail. The addition of uncertainty also stressed the frailty of making decisions based on only a slice of FBCE as was done in the baseline method. Incrementally adding each layer of uncertainty increased the breadth of uncertain futures considered. Ultimately this may help establish FBCE relevance as it increases a decision maker's confidence in the significance of any calculated FBCE differences.

Incorporating the selected correlations also had noticeable effects on the distribution of ADP. Given the preliminary nature of the work, quantitative conclusions seem inappropriate. However, the effects calculated highlight the value of obtaining better data to support further analysis.

Current regulation only requires that FBCE be calculated and reported for Acquisition Category Level I and II systems. In general, this includes only the more expensive acquisition programs.[60] This work found that sensitivity to energy costs seems significantly influenced by the system's service assumptions and the cost of a system relative to the cost of its wartime energy consumption. Further work is necessary to develop this quantitatively. If accomplished, this might allow refinement of the regulation that reduces workload burden for decisions less likely to be sensitive to FBCE and expands it for systems that likely are.

Additionally, the example used in this work, as established by current practice, assumed almost identical logistic chains. This assumption may be appropriate for generators but regulation and application should be expanded to perform FBCE calculations between systems with dissimilar logistic chains but similar capabilities. For example, a stateside bomber, forward deployed fighter or forward deployed drone may all be used to eliminate similar targets. To accomplish the same mission however, they each require different amounts of fuel and support that may need to be forward deployed and assume different amounts of risk for themselves and their support. If calculated, this comparison between mission cost, fuel use and risk assumed might create a very interesting decision for a military planner, of which FBCE would play a part.[61]

In its current form, the value of FBCE to an acquisition decision maker is highly dubious. It is incomparable to other costs and the importance of any calculated value relies on a decision maker's assumption of the modeled scenario's significance. As a consequence, FBCE is likely to

[60] The actual definitions of these categories are contained in Appendix B.
[61] Additional policy implications and recommendations are contained in Appendix B.

continue to be ignored, remaining only relevant in select offices for very specific purposes. Simply increasing the amount by which fuel costs are burdened does not resolve these issues.

Future work will continue the effort to overcome these obstacles to relevance by further altering the current framework. This framework must allow inclusion of non-linear efficiency effects and non-monetary outlays as well as exploration of scenario and joint significance. Maintaining non-monetary costs that can be averted may be particularly crucial towards developing relevance as individual decision makers are more sensitive to certain costs that are lost when converted to dollars. Potential casualties avoided is a non-monetary outlay of expected importance[62] but others could include avoided health care costs for the injured, greenhouse gas emissions and threat exposure hours.[63]

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[62] For the purpose of demonstration, initial analysis was presented in this work and will be expanded in future editions.
[63] Additional future work is contained in the Appendix.

A.6 References

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Appendix B: Fully Burdened Cost of Energy: Limitations and Value of Incentivizing Logistic Burden Addendum

B.1 Fuel Purchase as a Percent of Total DoD Outlays

As mentioned in the paper both the percent of outlays spent on fuel and the uncertainty in that quantity seem to grow from FY97-13. Figure B.1 shows the percent of total DoD outlays on fuel and Figure B.2 illustrates the percent change in DLA Fuel Spending and total DoD outlays [1]–[16].

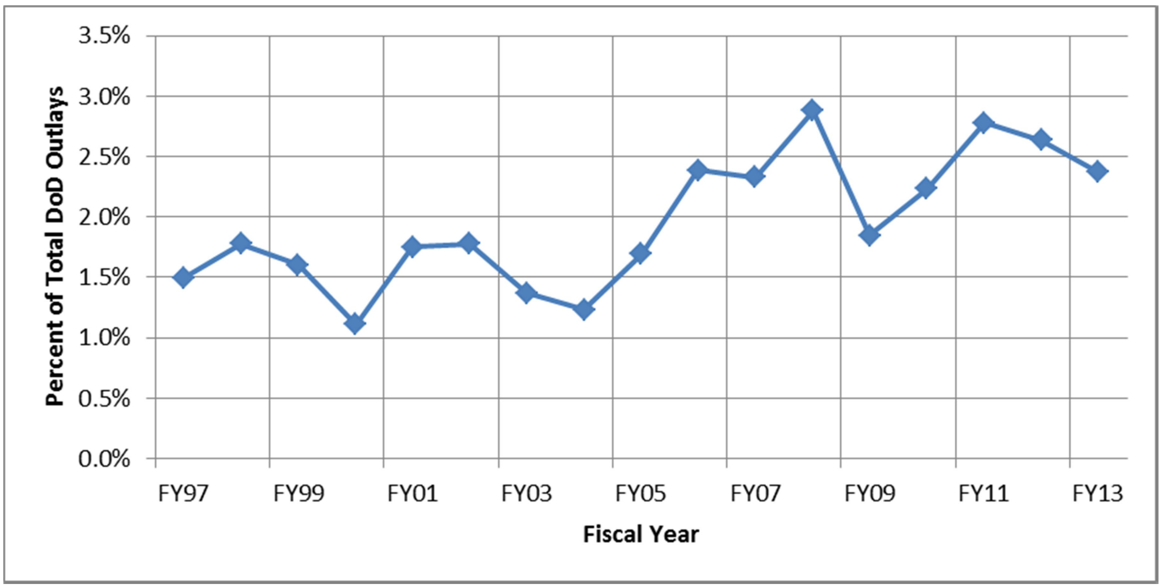

Figure B.1: Fuel Spending as a Percent of Total DoD Outlays

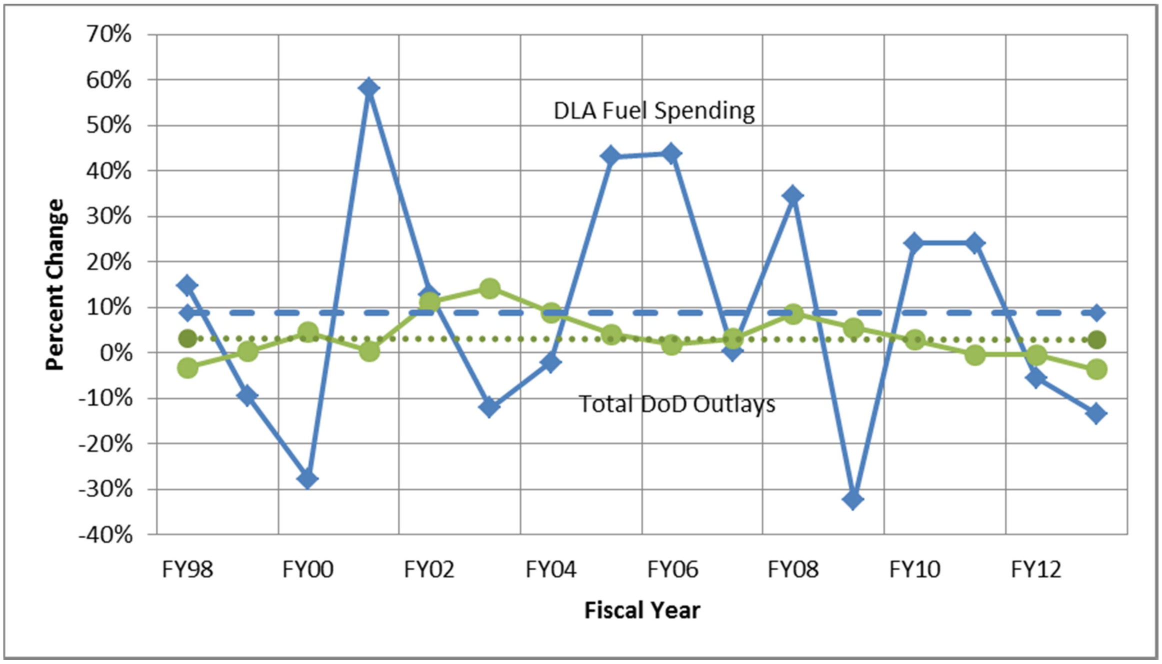

Figure B.2: Percent Change in DLA Fuel Spending and Total DoD Outlays

The first figure shows that average fuel spending as a function of total outlays is increasing over that time horizon. In the second figure, the dashed line represents the average percent change in fuel spending, while the dotted line represents the average percent change in total outlays. Accordingly, that figure illustrates that fuel spending growth is much more variable than other spending and growing at a faster pace on average.

Another potentially valuable way to view this fuel spending is to convert it to a per soldier intensity. Figure B.3 shows adjusted fuel spending in $1,000 per capita per fiscal year. The top two lines divide by the active duty force size while the bottom two incorporate Reserve and civilian numbers [17]–[25]. As the figure illustrates, recent spending intensity is near all-time highs dating back to FY91.

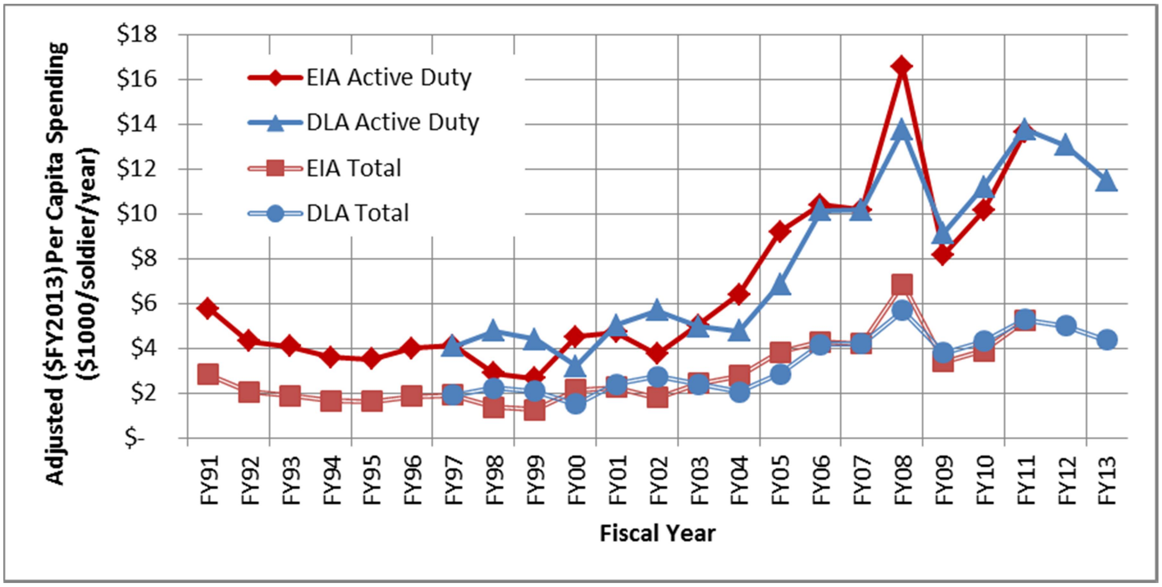

Figure B.3: Adjusted Per Capita Fuel Spending

However, there are several limitations to comparing this or other intensities. This is briefly discussed in the next section.

B.2 Growth of Fuel Consumption Per Soldier Over Time

Analysis conducted by Deloitte with data provided by DLA, the RAND Corporation, and the Army Materiel Systems Analysis Activity (AMSAA) found a steady increase in fuel consumption per soldier per day for US military engagements since WWII, shown in Figure B.4 [26].

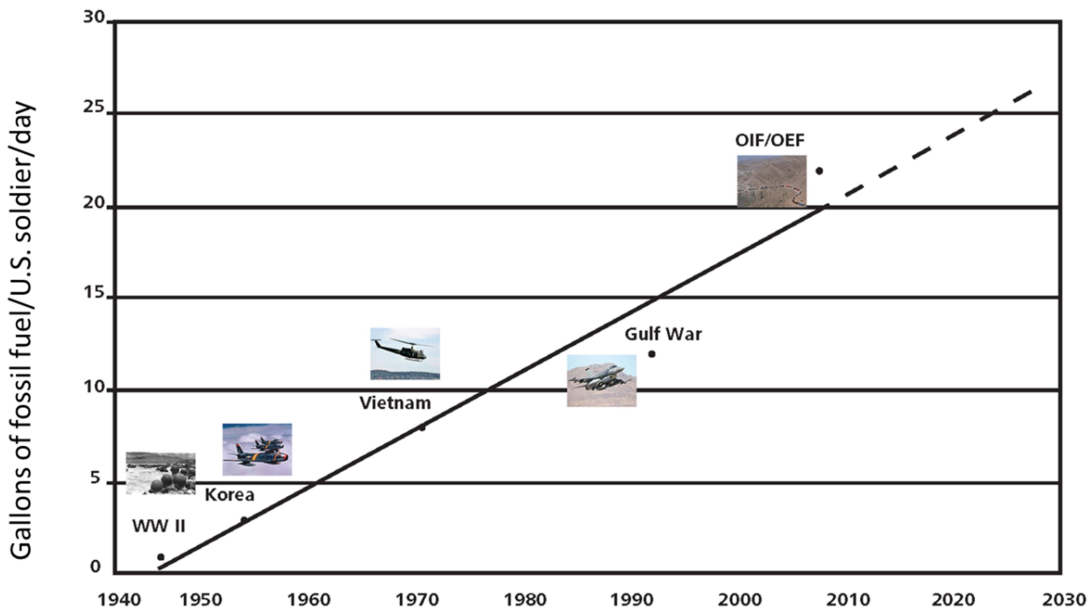

Figure B.4: Fossil Fuel Consumption Per-Soldier Per-Day (Modified figure from report)

While the indicated trend is concerning, the main issues are properly normalizing fuel consumption per soldier per day to some notion of per-soldier capability and mission value or quantity. The military is investing in hardware and software that may allow a single soldier to accomplish more "mission" in a given time. Accordingly, the figure really should divide by some concept of capability or number of missions. These ideas are very difficult to quantify in a way that enables direct comparison. For example, what was an average mission for an average soldier in WWII and how is that comparable to an average mission for an average soldier in Afghanistan today? Even in the same time frame comparison is difficult. Certainly there is a great difference in fuel used to fly supplies from A to B compared to a soldier detail that stands guard at an outpost in a theater of operations or even one that uses vehicles to patrol an area. The latter mission may rely on supplies available only because the first took place or not. Do these each constitute one mission or should they be weighted by difficulty or enemies killed or amount of supplies delivered? This author has neither the data nor the expertise to normalize this figure as it should be. As a result, the trend is interesting but potentially misleading.

B.3 Additional Information on Fully Burdened Cost of Energy

The Defense Acquisition Guidebook (DAG) states that Fully Burdened Cost of Energy (FBCE) is intended to "inform the acquisition tradespace by quantifying the per gallon price of fuel … used per day for two or more competing materiel solutions" [27].

While of similar intent, there are several definitions for FBCE within the DoD. The DAG defines it as "the cost of the fuel itself and the apportioned cost of all of the fuel logistics and related force protection required beyond the … DLA-E Energy point of sale" [27]. The National Defense Authorization Act (NDAA) FY2009 states that FBCE "means the commodity price for fuel plus the total cost of all personnel and assets required to move and, when necessary, protect the fuel from the point at which the fuel is received from the commercial supplier to the point of use" [28].

These two definitions certainly have overlap but the NDAA definition explicitly mentions a few items not contained within the DAG definition. The differences between and intentional flexibility within each of these definitions are some of the factors that have led to the large FBCE method variation seen across the DoD today.

B.4 History of FBCE

In the following reports, regulations and other documentation on FBCE, there is blurring of the line between fuel and energy and the introduction of the concept of operational energy. For the majority of this report, the report has attempted to explicitly differentiate these concepts. While important in certain contexts, the distinction is impossible to maintain while describing the evolution of the metric. A more detailed discussion of the differences and overlap between these is found in the next section.

The need for such a metric was first identified in a 1999 Defense Science Board (DSB) memorandum commissioned by the Office of the Secretary of Defense Acquisition, Technology and Logistics (OSD (AT&L)) [29]. Following that memorandum, several reports emerged stressing the critical importance of finding a way to incorporate a system's logistic footprint into the acquisition process and stem the alarming growth of operational energy demands [30]–[32]. A 2001 DSB report stated that "the task force found that these benefits [of energy efficiency], and the burden to warfighting capability of not focusing on efficiency, were not factored into decision-making." A JASON report put together by Dimotakis et al. remarked that

> "[f]uel use is characterized by large multipliers and co-factors...it takes fuel to deliver fuel….[It] imposes large logistical burdens, operational constraints and liabilities and vulnerabilities: otherwise capable offensive forces can be countered by attacking more-vulnerable logistical-supply chains."

Finally, a report by Crowley et. al. identified three major areas of disconnect between the DoD's current energy consumption practices and the capability requirements of its energy strategy. First, dependence on foreign fuel limits the DoD's strategic flexibility when "dealing with producer nations who oppose or hinder our goals for greater prosperity and liberty". Next, DoD operational goals have resulted in significant energy consumption with predicted upward trends. Lastly, the report recommended bridging the fiscal disconnect, in part, by

> "incorporate[ing] energy considerations (energy use and energy logistics support requirements) in the department's key corporate processes: strategic planning, analytic agenda, joint concept and joint capability development, acquisition, and planning, programming, budgeting, and execution (PPBE)" [32]

Despite these reports, it was not until the middle of 2007 that two offices within OUSD tried to establish such a metric. In April 2007, OUSD (AT&L) released a memorandum that established three pilot programs to test a then unestablished framework and stated that

> "[e]ffective immediately, it is DoD policy to include the fully burdened cost of delivered energy in trade-off analyses conducted for all tactical systems with end items that create a demand for energy and to improve the energy efficiency of those systems, consistent with mission requirements and cost effectiveness" [33].

A few months later, OUSD Program Analysis and Evaluation (PA&E) released a memorandum that created a rudimentary methodology for Fully Burdened Cost of Fuel (FBCF) [34].[64]

Even still, a DSB report released in February 2008 reached several important conclusions, including:

> "The Department [of Defense] has no consistent methodology to simulate the battlespace conditions created by high fuel re-supply requirements during campaign analyses, war gaming or staff training exercises. This makes fuel supply consequences invisible to operations and force planners."

> "DoD has not yet fully implemented two key recommendations from a 2001 DSB Task Force on energy – establish a Key Performance Parameter (KPP) to constrain battlespace fuel demand; and establish the fully burdened cost of fuel (FBCF) to guide acquisition investments for deployed systems. This Task Force recommends the Department accelerate implementation of these, and that the Deputy Secretary exercise oversight" [35].

In response to this and other reports, OUSD (AT&L) issued a memorandum in July 2008 that reinforced the implementation of FBCF into the KPPs and life cycle management framework [36]. This was later incorporated into mandatory DoD instruction (DODI) 5000.02, the National Defense Authorization Act (NDAA) for FY2009, and the Weapon Systems Acquisition Reform Act (WSARA) [28], [37], [38]. The Department's support of the concept was further demonstrated when it published the 2010 Quadrennial Defense Report and an update

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[64] While the intent of the concept remained unchanged, FBCF was eventually renamed Fully Burdened Cost of Energy (FBCE) to reflect the understanding that not all military energy is fuel.

to the Chairmen of the Joint Chiefs of Staff (CJSCI) 3170 manual [39], [40]. In July 2012, OUSD (AT&L) issued its last guidance on FBCE methodology with the goal of providing consistency between service calculations [41]. The latest version of the DAG states that FBCE calculations

> "shall be made and reported for all acquisition category (ACAT) I and II systems that will demand fuel or electric power in operations and will be applied to all phases of acquisition beginning with the preparation of the Analysis of Alternatives (AoA)" [27].[65]

B.5 Interchangeability of Energy and Petroleum for the DoD

Founding studies on quantifying logistic footprint of end-user energy demand focused on petroleum fuel for several reasons. Possibly the two most important ones are that they are by far the largest source of DoD energy and, given their relative ease to store, high energy density, and ability to be transported, represent the most likely option to satisfy the energy needs of operational forces. This is especially true for those at the edges of the battlespace where logistic lines are the costliest. From these initial reports, the concept of FBCF was created. Eventually, regulations and guidelines began to recognize that not all energy was fuel and changed the name of the metric from FBCF to FBCE, while the core concept of the metric remained unaltered. Later, the 2009 NDAA formalized, the concept of "operational energy" as "the energy required to train, move, and sustain military operations" [28].[66]

By looking at available information on energy sources, it is possible to estimate how interchangeable "operational energy", FBCE, and FBCF are in practice. A 2012 Congressional

[65] The definitions for the various acquisition categories are contained later in this Appendix.
[66] In practice, some offices treat operational energy as the energy required for combat or wartime military operations, in contrast to training or peacetime operations. Others treat the counter to operational energy as installation energy, or the energy used to support installation infrastructure.

Research Service (CRS) report determined that petroleum accounted for 71% of total DoD energy use in FY2010 [42]. This and other energy allocations are shown in Table B.1. The DoD Operational Energy Strategy cites that approximately 75% of total energy use is for operations with the remaining 25% supporting installations [43]. Table B.2 shows the breakdown of installation energy use as reported by the Office of the Deputy Under Secretary of Defense (Installations and Environment) (DUSD (I&E)) [44]. The DUSD (I&E) report does not break up energy use into the same categories as the CRS report. For the sake of this calculation, fuel oil, LPG, propane, and other installation energy are lumped together to give a conservative representation of petroleum usage. Additionally, installation steam energy is associated to the CRS report's "Other" category.

Table B.1: Energy Allocation in FY2010

% of Total Energy Use in FY2010	
Petroleum	71%
Electricity	11%
Natural Gas	8%
Nuclear(Navy ships)	7%
Coal	2%
Other	1%

Table B.2: Installation Energy Use

Installation Energy	% of Use
Fuel Oil/LPG/Propane/Other	13%
Electricity	44%
Natural Gas	32%
Coal	8%
Steam	3%

Using this information, an approximation of the allocation of operational energy is possible. Table B.3 shows the results. With the reported values, this estimate found that electricity, natural gas, coal and other contribute trivially to operational energy and, for this level of accuracy are indistinguishable from zero. The "missing" 1% is scattered throughout. Clearly, the vast majority of operational energy needs are met with petroleum products, making the distinction between energy and fuel important to remember but nonessential for most first-order analysis of an operational energy metric.

Table B.3: Operational Energy Use

Operational Energy	% of Use
Petroleum	90%
Nuclear (Navy ships)	9%

B.6 Scenario Dependency of Logistic Chains

As stated, the comparison of two competing systems' FBCE is highly dependent on their expected use in a future operational environment. Both expected use and future operational environments can be functions of each other. Figure B.5 shows a notional operational environment and its associated logistic chain, referred to in its entirety as a scenario. Located in theater, some system creates a fuel demand that is met through fuel purchases at a point of sale. Fuel convoys, and all the other necessary infrastructure and supporting assets, then deliver the fuel from the point of sale to the fuel demand location. Escort assets may directly assist this delivery because of the chance of enemy interdiction within the combat delivery zone. As shown, the cost per gallon to deliver fuel is a function of many uncertain variables in the future scenario, such as number and type of delivery assets (shown with fuel trucks but could be other ground, air or sea assets), distance from the point of sale to the demand location and need for, type of and quantity of escort assets. Modeling these uncertainties creates a distribution for the cost of delivered fuel.

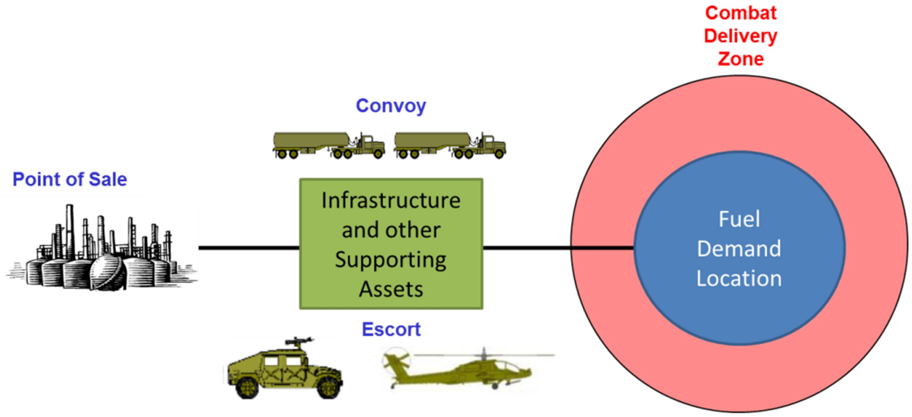

Figure B.5: Notional Military Logistic Chain

B.7 Portion of Total DoD Fuel Use in Iraq and Afghanistan

As mentioned, FBCE models future scenarios that represent operational environments. In practice, these operational environments are intended to model potential wartime logistic chains because peacetime ones assume demand is at the point of sale. In reality, most peacetime usage requires some DoD-owned logistic support, though most likely much less significant than wartime. Because it is disregarded in current practice, this report focuses on the potential effects of FBCE for only wartime usage. As a result, FBCE adds costs to only a portion of the spending illustrated in Figure A.1.

Figure B.6 shows an estimate of fuel purchased in Iraq and Afghanistan as reported by DLA from FY01 to FY08, which likely represent a significant portion of wartime demand during this period [4]–[11]. These values and the number of "boots on the ground" in theater were used to extrapolate the fuel purchased in these theaters through FY13 [45].

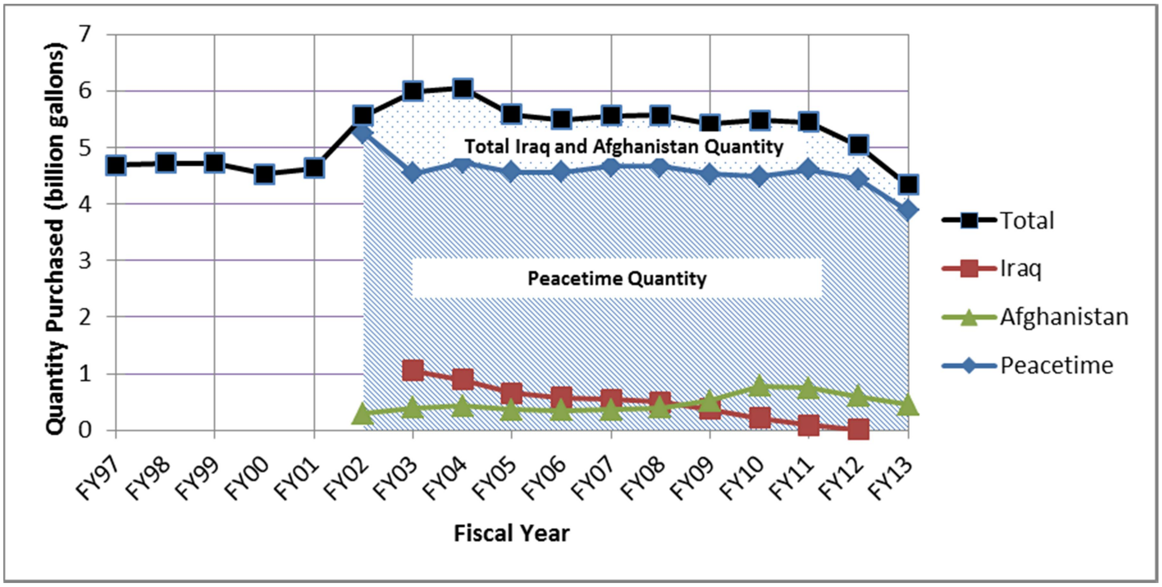

Figure B.6: Total, Iraq, Afghanistan and Peacetime Quantity of Petroleum Products Purchased

It should be noted that these estimates are unable to account for the potentially significant use of fuel by supporting forces that purchase it and are officially stationed outside of these theaters.

Even still, this estimate demonstrates that a large portion of the increases in fuel quantity from FY01-13 are attributable to operations in Iraq and Afghanistan, relatively small, albeit geographically distant, operations.[67] Some of the quantity used in theater is for combat operations and some is for the logistics supporting combat operations. In peacetime, neither would exist. Ultimately, better understanding the ratio between the two is desired.[68] Additionally, this portion of fuel use is much more sensitive to future uncertainties than peacetime use. All of which add to the potential value of FBCE to the DoD.

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[67] General Schwarzkopf's five day maneuver used an estimated 30% of the 8-10 billion gallons of fuel consumed by the DoD in FY91.

[68] Indirectly, the data also shows higher fuel intensity per troop in theater. Over these years, fuel purchased in Iraq and Afghanistan averaged around 16% of total DoD purchase (range 5% to 24%). While on average, only around 10% of the total active duty force or 4% when including Reserve members and DoD civilians were located in theater [17]–[25].

B.8 Current State of FBCE

While there have been many memorandums and regulations requiring the adoption and calculation of FBCE, actual usage and development has been mixed at best. Because of multiple offices and services mentioned in this section, an organizational chart for the DoD is included for reference in Figure B.7 [46].

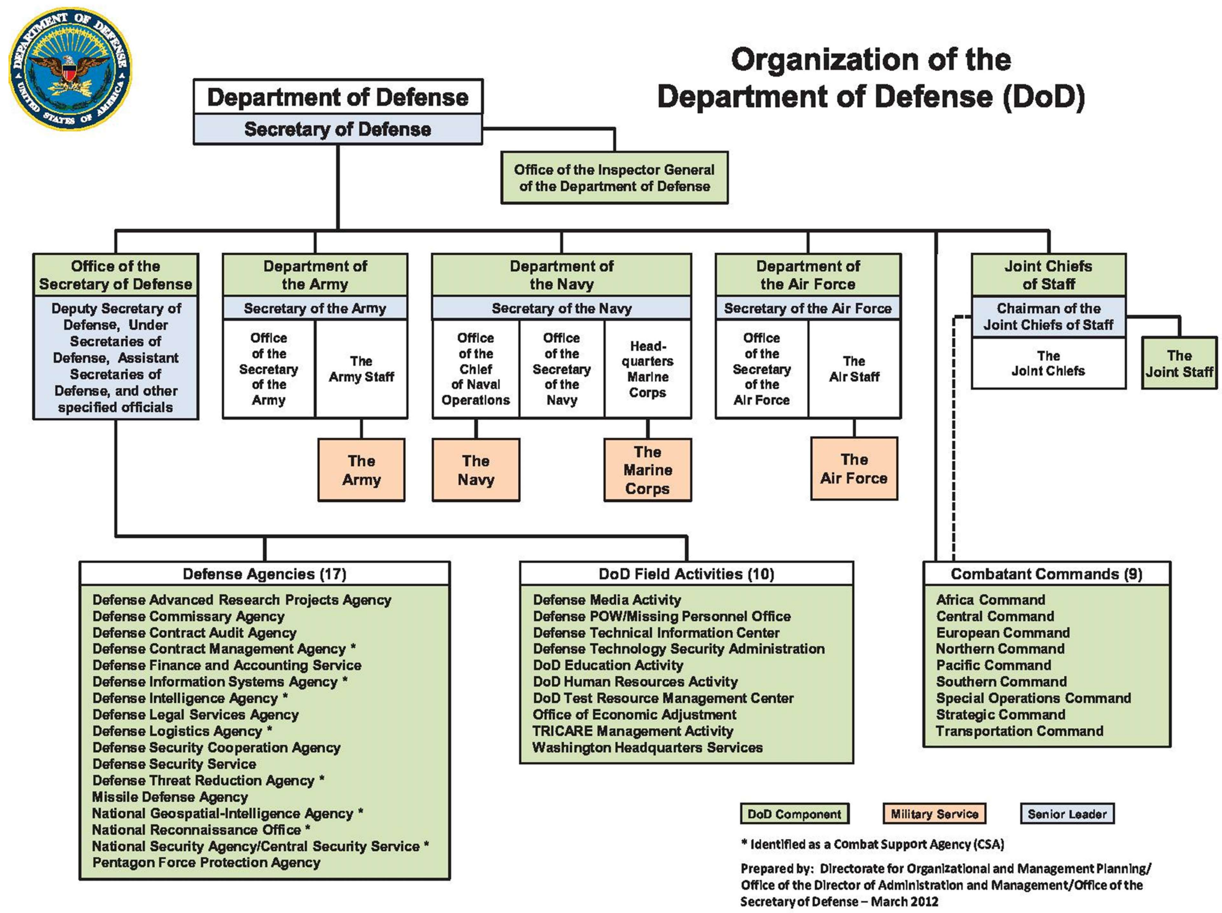

Figure B.7: Organization of the Department of Defense

Attempting to clarify the process, OUSD (AT&L) released a prototype fully burdened cost of fuel (FBCF) calculator in 2010. The prototype was originally embraced by the Navy and Marine Corps, while the Army and Air Force followed a similar methodology but developed their own.

The OUSD (AT&L) calculator uses Monte Carlo simulation to determine the distribution of FBCE within a scenario, determined by input parameters.

The Air Force calculator is a deterministic calculator that incorporates data from the Air Force Total Ownership Cost (AFTOC) database, the Capital Asset Management System (CAMS-ME) and the Secretary of Defense for Installations and Environment (DUSD (I&E)) Facilities Assessment Database.

The Army developed two models for different end uses. The Deputy Assistant Secretary of the Army for Cost and Economics (DASA-CE) model is a top-down macroeconomic model removed from certain scenario dependencies and used to satisfy regulatory requirements during the Analysis of Alternatives (AoA) phase of acquisition. The Logistics Innovation Agency (LIA) model is a bottom-up microeconomic model that could be used to support tradeoff analysis.

Since 2012, support for and investment in FBCE has waned for all but the Army. Given the large number of parameters and the very wide distribution ranges it generated, OUSD (AT&L)'s calculator was difficult to implement and seems to have fallen out of use. No updates after 2011 have been found. While previously working to demonstrate the value of the concept at the Naval Post Graduate School, the Navy and Marine Corps show no current interest in developing FBCE and have conducted no significant work recently [47]–[51]. The Air Force used its earlier work to justify issues with and inadequacies of the metric. They have published no significant updates to their model since 2010. In contrast, the Army continues to fund and develop their calculators and the underlying methods.

B.9 FBCE Method Demonstration

The scenario is constructed from a notional theater layout as described by the Capabilities Development Team, US Army Combined Arms Support Command (CASCOM). This scenario includes fuel-delivery and escort assets as well as several delivery support assets required for fuel missions from the point of sale to the energy-demanding system. The assets in this scenario are discussed in more detail in the Appendix. The quantity and allocation of costs for all fuel-delivery and support assets are normalized to a 60-truck fuel convoy with a capacity of about 350,000 gallons per delivery. The quantity and allocation of costs for the escort assets represent what the guidance assumes for a “high risk” delivery in this scenario [52].

The developed model is based off of Force and Organization Cost Estimating System (FORCES) data and an existing framework created by the US Army [52], [53]. Within this framework, yearly peacetime costs for each asset are determined from FORCES data, which contains direct equipment, personnel, indirect support and acquisition costs. While personnel costs include many expenses, the framework does not directly value human life. The summation of these costs is divided by an assumed training days per year to determine a daily peacetime cost. This is converted to costs per scenario day using equipment and personnel cost factors. Total cost per scenario day is converted to a deterministic ADP through a series of parameters. Initially, all cost factors and parameters are assumed from the previously cited works. This framework, the parameters, and their initial values are shown in Table A.2. Overall, this model accounts for the operations and support and depreciation costs of fuel-delivery, fuel-delivery support and escort assets. All other potential costs mentioned in OEPP’s guidance are ignored. Additionally, current models ignore the feedback loop in Figure A.3, meaning ADP and risks are independent of the amount of fuel demanded.

B.10 Existing Method Assets and Allocation

Table B.4 shows the quantity and allocation of costs for all assets assumed in a current method. The assets can be generally grouped into the following three groups: fuel delivery support assets, fuel delivery assets and escort assets.

Table B.4: Quantity and Allocation of Assets in Notional Scenario

Asset Name	Quantity	% Allocation of Total Cost
Headquarters and Supporting Personnel	1	0%
Tactical Petroleum Terminal	1	100%
Petroleum Terminal Personnel Type A	1	100%
Petroleum Terminal Personnel Type B	1	100%
Other Tactical Infrastructure	1	100%
Tactical Headquarters	1	0%
Forward Support –Ground Forces	2	15%
Forward Support –Artillery	1	15%
Forward Support–Reconnaissance	1	15%
Fuel Trucks Type A Unit	1	100%
Fuel Trucks Type B Unit	1	100%
Fuel Trucks Type C Unit	1	100%
Escort Asset–Ground Forces	2	100%
Escort Asset–Aerial Scout	1	50%
Escort Asset–Attack Helicopter	1	50%

All the assets in the table from "Headquarters and Supporting Personnel" down to "Forward Support—Reconnaissance" represent fuel delivery support assets. Their quantity and allocation of total costs are normalized in the current method to a 60 fuel truck convoy. As the two headquarters listed serve many roles for many missions, their allocation of total cost for any particular fuel delivery is assumed negligible and ignored.

In this scenario, the three types of fuel trucks are the only fuel delivery assets. Each unit represents roughly 20 trucks but the types have different capacities and total costs.

There are three escort assets included in the examined method. Unlike the other assets, their quantity and allocation of total costs are not normalized to the fuel convoy. For the escort assets, the factors are related to a mission planner's subjective assessment of risk. Initial analysis assumed the quantities and costs associated with the available guidance's "high-risk" scenario [52].

B.11 Value of Personnel Description and Work

B.11.1 Description

In the current method, there is no direct incorporation of the value of personnel. Similar to escort assets, personnel represent high value investments of training and experience. The loss of which, if modeled, may significantly alter the cost of delivering fuel. Unlike escort assets, there is a normative value to personnel that extends beyond their operational utility. Accordingly, this report does not assume a value of statistical life or otherwise attach a monetary value to human life. Based on available data and other assumptions, initial analysis attaches a casualty rate to the calculated cost per gallon, creating a multi-attribute cost for the decision maker.

B.11.2 Work

This section assumes the current model's quantity of assets and allocation of costs. The number of personnel represented by the asset type is derived from publicly available data and shown in Table B.5 [54].

Table B.5: Number of People in Logistic Chain

Asset Name	Quantity	Cost Allocation	People	
			Minimum	Maximum
Tactical Petroleum Terminal	1	100%	100	200
Petroleum Terminal Personnel Type A	1	100%	100	200
Petroleum Terminal Personnel Type B	1	100%	16	40
Other Tactical Infrastructure	1	100%	500	600
Forward Support –Ground Forces	2	15%	100	200
Forward Support –Artillery	1	15%	100	200
Forward Support–Reconnaissance	1	15%	100	200
Fuel Trucks Type A Unit	1	100%	20	40
Fuel Trucks Type B Unit	1	100%	20	40
Fuel Trucks Type C Unit	1	100%	20	40
Escort Asset–Ground Forces	2	100%	16	40
Escort Asset–Aerial Scout	1	50%	1	2
Escort Asset–Attack Helicopter	1	50%	2	4

The average casualty rate is parametrically analyzed across various asset loss rates, where escort asset losses are assumed to a magnitude of order less than other assets. The results are shown in Table B.6 per 350,000 gallon delivery and per gallon.

Table B.6: Average Casualty Rates Per Delivery and Gallon

Loss Probability		Average Casualty Rate	
Escort Asset	Other Asset	Per Delivery	Per Gallon
1.0%	10%	110	3.0E-04
0.50%	5.0%	53	1.5E-04
0.10%	1.0%	11	3.0E-05
0.010%	0.10%	1.1	3.0E-06

Even at low loss rates, there are appreciable casualties. Weighing the importance of averting casualties against monetary costs is left to the decision maker.

B.12 Non-Linear Interaction Between ADP and Demand

In the short term, if the current personnel and equipment supporting fuel delivery is near capacity, only small increases in demand will be able to be satisfied (e.g., additional trucks and drivers are not available). Pushing towards capacity might require quick turn-around times foregoing preventative maintenance, crew rest, safer but longer routes and the support of escort assets. Each of these would in turn increase the per gallon price of fuel, as the probability of mechanical failure and enemy loss increased.

In the long term, significant increases in fuel demand would require the acquisition and transport to theater of more fuel-delivery and fuel delivery support assets, such as fuel trucks. Not only do they consume fuel themselves, but more fuel trucks require more trained operators and maintainers. These new personnel in turn need logistical support, such as food, water and shelter, all which take fuel to deliver.

B.13 Uncertainty in ADP

The first group includes all available escort assets (e.g., aerial scouts and attack helicopters). Both their quantity and the percent of total costs attributable to fuel delivery are variable. Fundamentally, escort assets represent one of many methods to mitigate the expected risk of fuel delivery through a combat zone. However, escort assets are a limited resource that can support many different missions. As their frequency of use for fuel delivery fluctuates relative to their total use so moves the percent of total costs properly apportioned to the fuel itself. Additionally, the quantity of escort assets assigned to support a fuel delivery chain is not causally linked to the frequency of deliveries if there are other methods to avoid the risk (e.g., randomized delivery routes and schedule). Even as risk for fuel delivery increases and other methods of mitigation are unavailable or ineffective, the quantity of escort assets assigned to fuel deliveries is variable if higher priority missions arise or escorts are otherwise unavailable. These relationships are addressed by assigning distributions to the quantity assigned and parametrically analyzing sensitivity to the allocation of total costs.

The second group represents the fuel delivery support assets and consists of all the remaining scenario forces except for the fuel trucks (e.g., fuel terminal and personnel and forward support forces). These fuel delivery support assets have already been normalized to the fuel demand so their quantity is held constant to the baseline. However, it is assumed that the modeled assets exist as a part of a larger infrastructure. Accordingly, the percent of their total costs allocable to a single fuel delivery chain is a function of end-user demand and other asset uses. This relationship is simpler than that of the first group and its sensitivity is analyzed parametrically.

The third group includes the fuel trucks. It is assumed they serve no operational purpose other than delivering fuel. While the allocation of costs for the rest of the assets may vary as a function of demand and other factors, the total cost of operating a fuel truck is allocated to the fuel user that requires its operation.[69]

B.14 Establishing Ranges for Parameter Distributions

The following outlines the data used and assumptions made to fit distributions to the parameters.

For this initial work, the distribution for "Personnel Factor" was thoroughly explored to determine the feasibility and value of such work as data for this parameter was readily available. At this time, the other parameters' mean or mode was assumed from available military guidance or other reports [52], [55]. The distribution type was chosen based on the nature of the parameter

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[69] In reality, fuel trucks can be used to service multiple operations at the same or different locations. For this initial work, this possibility is ignored and the normalized fuel convoy is sent as often as needed to satisfy the fuel demand of a single end-user at a single location.

(e.g. discrete uniform for asset quantity parameters and triangle distributions for others). Bounds were assumed to assess sensitivty to the various parameters and prioritize future work.

The “Personnel Factor” parameter is attempting to quantify the percent of additional pay earned by military personnel in a wartime scenario. Peacetime military pay was assumed to consist of base pay, basic allowance for housing (BAH), and basic allowance for subsistence (BAS). Military clothing allowance is assumed insignificant and is ignored. A FY2012 DoD demographic report gives the distribution of the active duty force across pay grade with around 16%, 1% and 83% spread across the various officer, warrant officer and enlisted grades, respectively [25]. The pay grade percentages are then used to appropriately weight published FY2012 base pay, basic allowance for housing and all other pay grade dependent salary [56]–[58]. Base pay is also a function of time of service, which is conservatively distributed to match published US Air Force service averages of 8 years for enlisted and 11 years for active duty [59]. Air Force service averages were assumed representative of the organization as averages across the entire DoD were not found. This resulted in a weighted average base pay of around $3,260 per month.

Besides pay grade, the BAH is also a function of location and dependents. Each published location was assumed equally likely. The organization wide average of military members with dependents of 44% was assumed across all pay grades. This resulted is a weighted average BAH of $1,170 per month.

BAS is differentiated between officer and enlisted. Using the previously determined percentages, the weighted average BAS is $330 per month across the DoD.

Incentive combat pay is assumed to consist of hardship duty pay (HDP), assignment incentive pay (AIP), hazardous duty incentive pay (HDIP), hostile fire/imminent danger pay, and family separation allowance. The tax incentives of being in a theater of operation are ignored. HDP and AIP are payable at different levels depending on location and career type. The available levels are used to represent minimum, most likely and maximum values and are shown in Table B.7.

Table B.7: HDP and AIP Distribution

	Min	Most Likely	Max
HDP	$50	$100	$150
AIP	$75	$100	$3,000

HDIP is constant across pay grades for non-aircrew personnel but not for aircrew. After weighting the aircrew incentive pay by grade and assuming a uniform 20% aircrew across the organization, the weighted average HDIP is around $160 per month.

Hostile fire/imminent danger pay and family separation allowance are $225 and $250 per month, respectively.

Table B.8 shows a summary of the calculation.[70] As demonstrated, the range in personnel cost increase is large and even the minimum calculated increase is greater than the 10% assumed in the baseline.

Table B.8: Summary of Increase in Personnel Costs

Weighted Average (Per Month)	Value (FY2012$)	Increase (FY2012$)	Personnel Factor
Peacetime	$4,800	-	
Minimum Wartime	$5,500	$760	16%
Most Likely Wartime	$5,600	$830	17%
Maximum Wartime	$8,500	$3,800	79%

[70] The details of the calculation and assumptions are found in the Appendix.

B.15 Uncertainty in Load and Peak Load Profiles

Trend lines were fit to publicly available fuel consumption data for the two generators cited in the main paper [60], [61].[71] The data and trend lines are shown in Figure B.8, where load factor is defined as the current electrical output as a percent of the generator's maximum output.

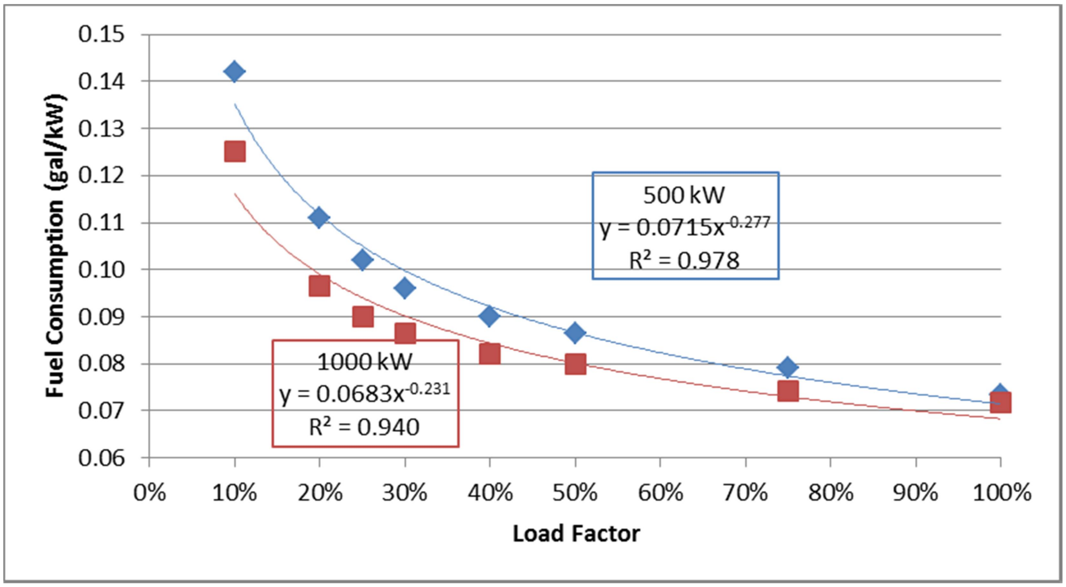

Figure B.8: Generator Fuel Consumption vs. Load Factor

Figure B.9 shows the load curve assumed in the main paper scaled to a peak load of 1,000 kW [62].

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[71] A separate analysis for a similarly sized engine was used to extrapolate fuel consumption for lower load factors, as the manufacturer only published fuel-consumption data down to a 50% load factor [64]

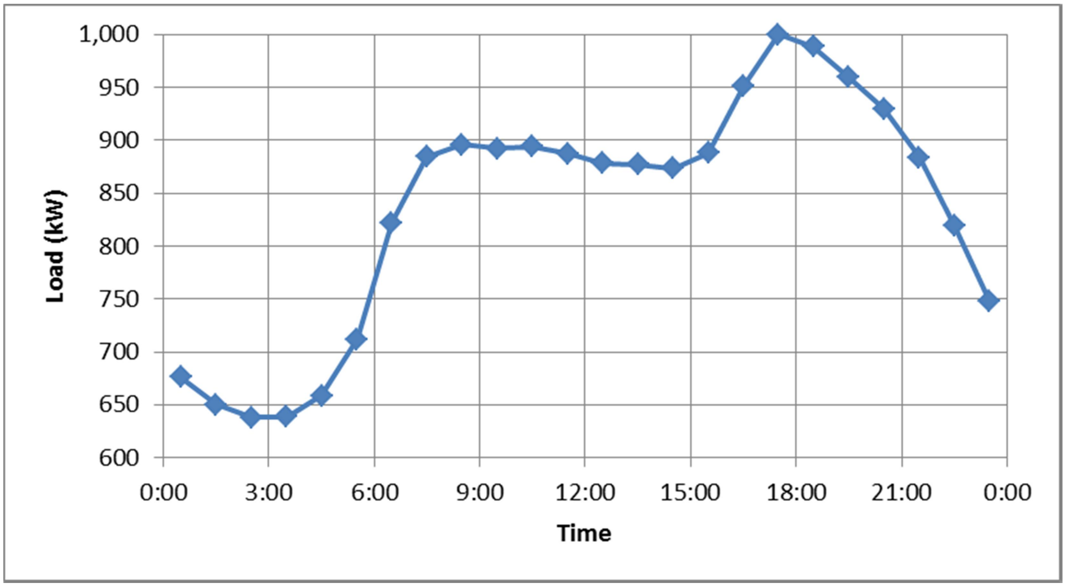

Figure B.9: Scaled Load vs Time

Analysis calculated the fuel used by each generator alternative to satisfy this peak load curve scaled from 2 to 1,000 kW, shown in Figure B.10. The figure shows the 500 kW generators' area of greater efficiency ranges from a peak demand around 50 kW to 710 kW.

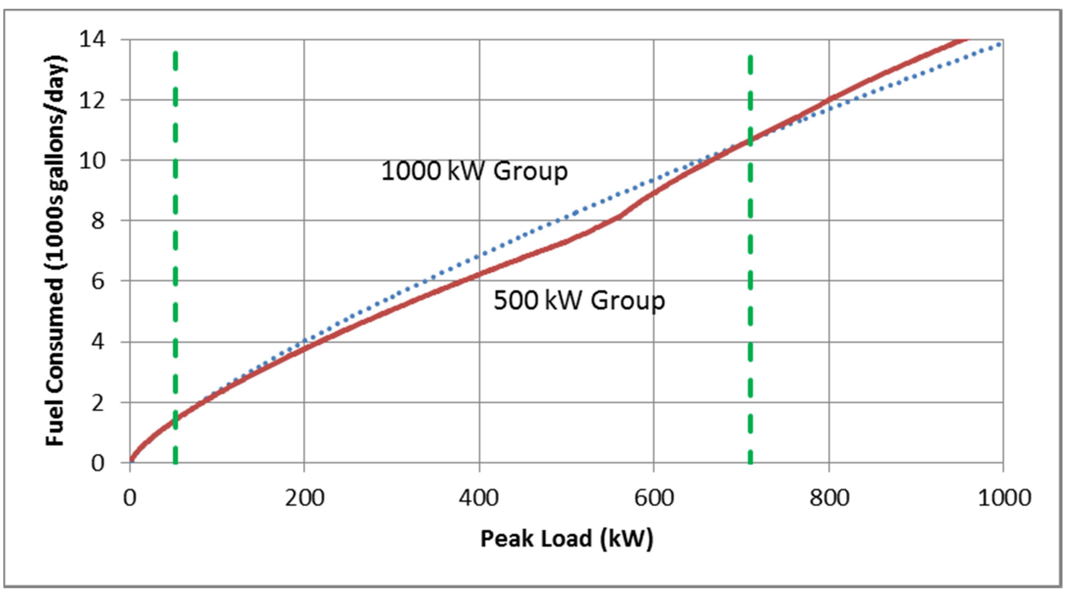

Figure B.10: Fuel Consumed Per Day vs Peak Load Curve

Figure B.11 shows the difference in fuel consumed by the generator alternatives multiplied by the base cost ($4/gallon) and deterministic FBCE ($9.75/gallon). A negative difference indicates that the 500 kW alternative is preferred.

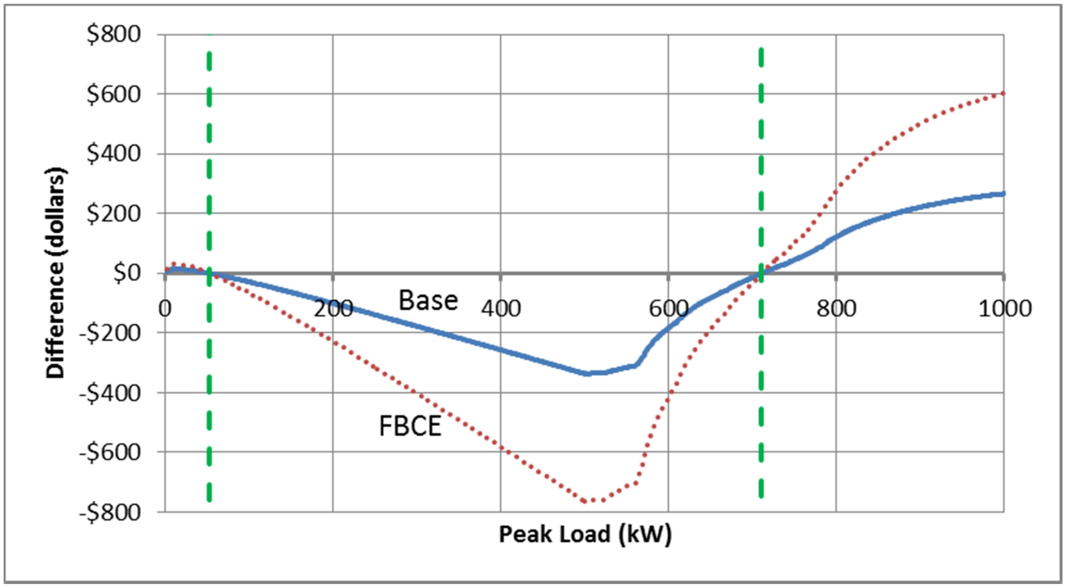

Figure B.11: Base Cost and FBCE Difference

The figure shows that the 500 kW alternative is preferred to the 1000 kW if all peak loads are equally likely. However, if the lower peak loads were actually feasible, the 1000 kW alternative would probably not be a reasonable option in the first place. This is expanded in the next section.

B.16 Uncertainty in Demand

The two peak load probability profiles shown in the main paper are reproduced in Figure B.12.

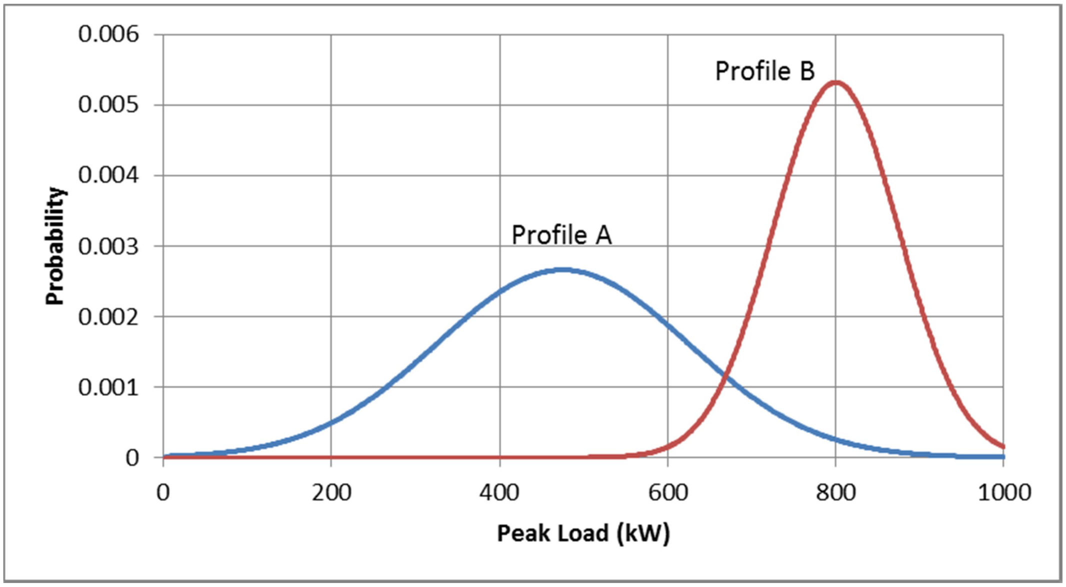

Figure B.12: Peak Load Probability Profiles

The procedure outlined in the previous section is conducted again but now the cost difference calculation is weighted by the profiles. Assuming the same deterministic ADP, the results are illustrated in Figure B.13. The 500 kW alternative is preferred for Profile A and the 1000 kW alternative for Profile B. However, the magnitude of preference and regret differs between the profiles.

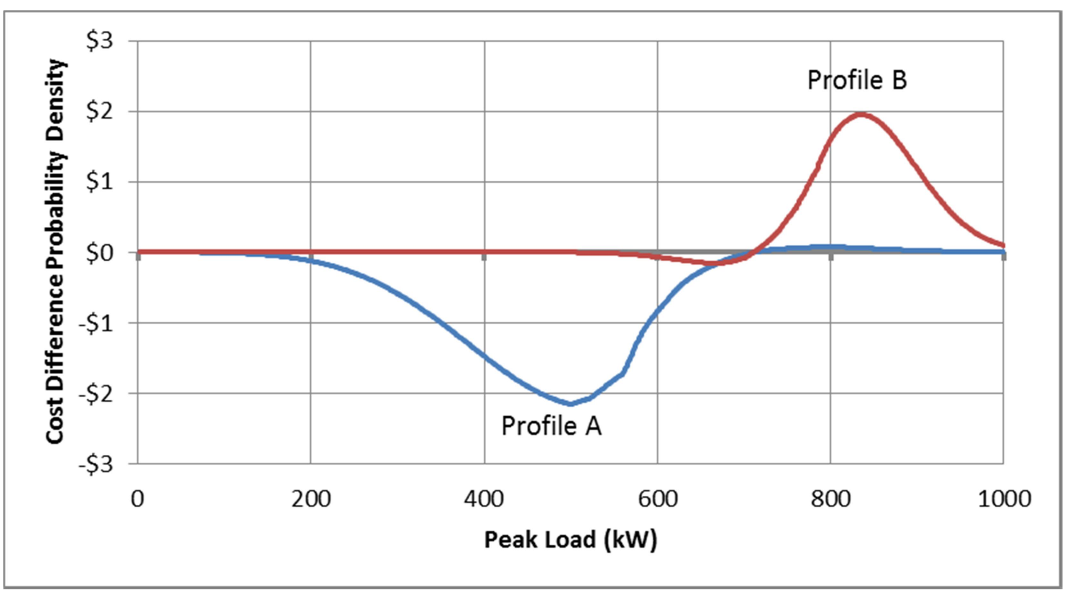

Figure B.13: Cost Difference Probability with Deterministic ADP

Figure B.14 shows the effect of incorporating an uncertain ADP, where the shaded area represents the range between the 10^{th} and 90^{th} percentile. The 500 kW alternative is still preferred for Profile A and the 1000 kW alternative for Profile B. However, the magnitude of the preference distribution for the 500 kW alternative in Profile A is always greater across all percentiles than that for the 1000 kW alternative in Profile B. In other words, if both profiles are equally likely, the 500 kW alternative is preferred.

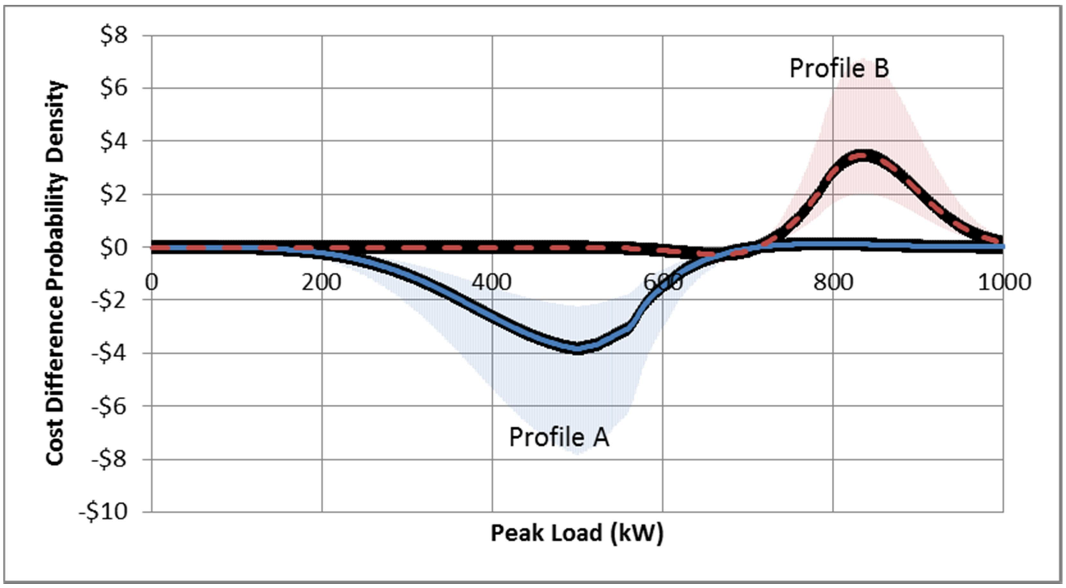

Figure B.14: Cost Difference Probability with Uncertain ADP

B.17 Uncertainty in ADP and Demand Interaction

The figure with the three functional relationships assumed between ADP and fuel demand in the main paper is reproduced below.

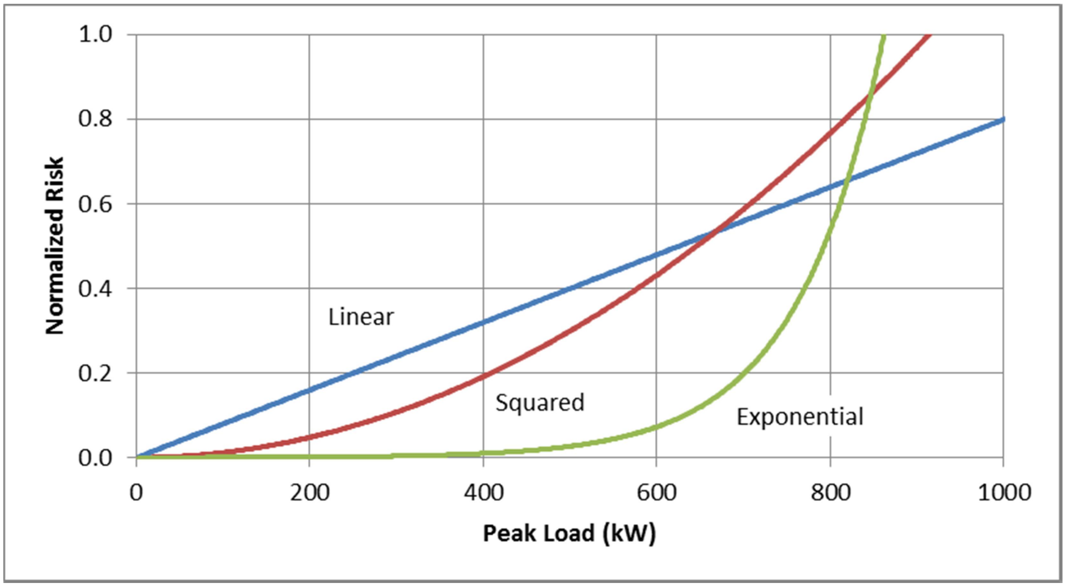

Figure B.15: Normalized Risk vs. Peak Load

As before, the per-day fuel demand for each peak load curve is calculated for each generator alternative and then multiplied by the probability of requiring that peak load and the risk-dependent ADP. The figures below show the risk-dependent ADP and resulting cost difference PDFs for the linear and squared functional relationships.

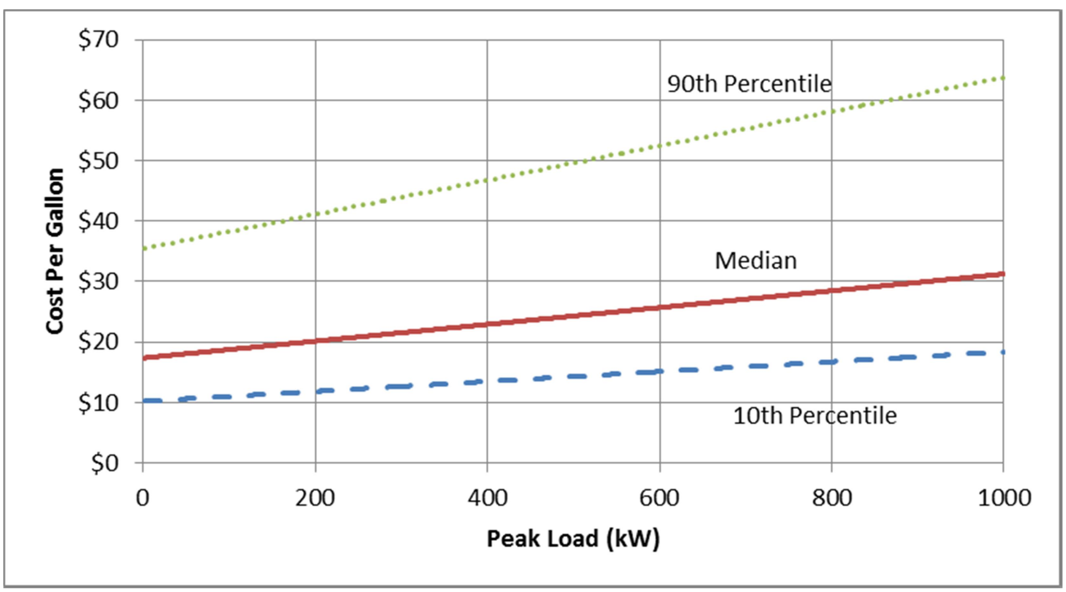

Figure B.16: Linear Risk-Dependent ADP vs Peak Load

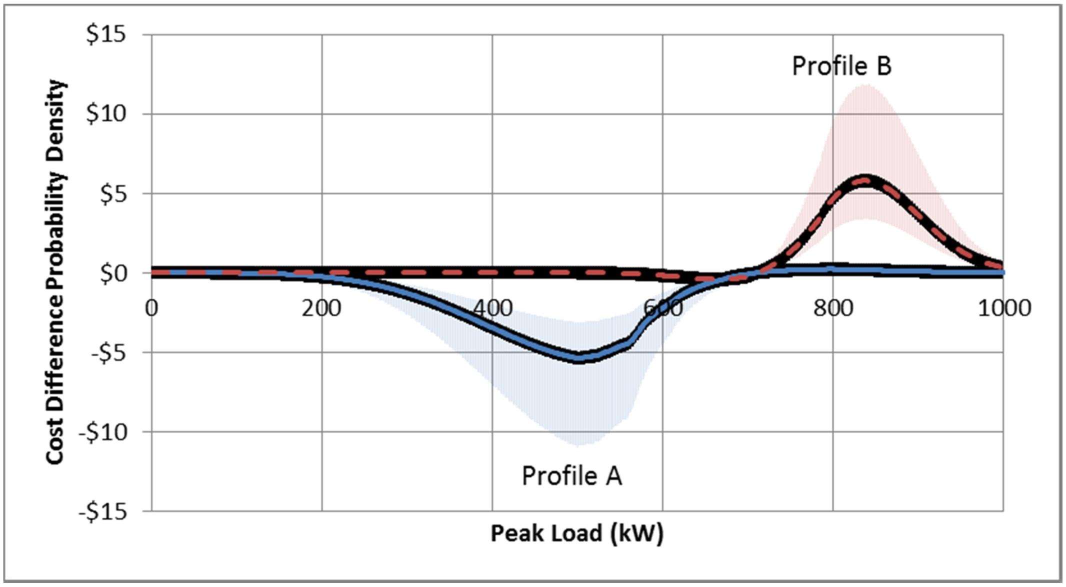

Figure B.17: Linear Cost Difference Probability Density vs Peak Load

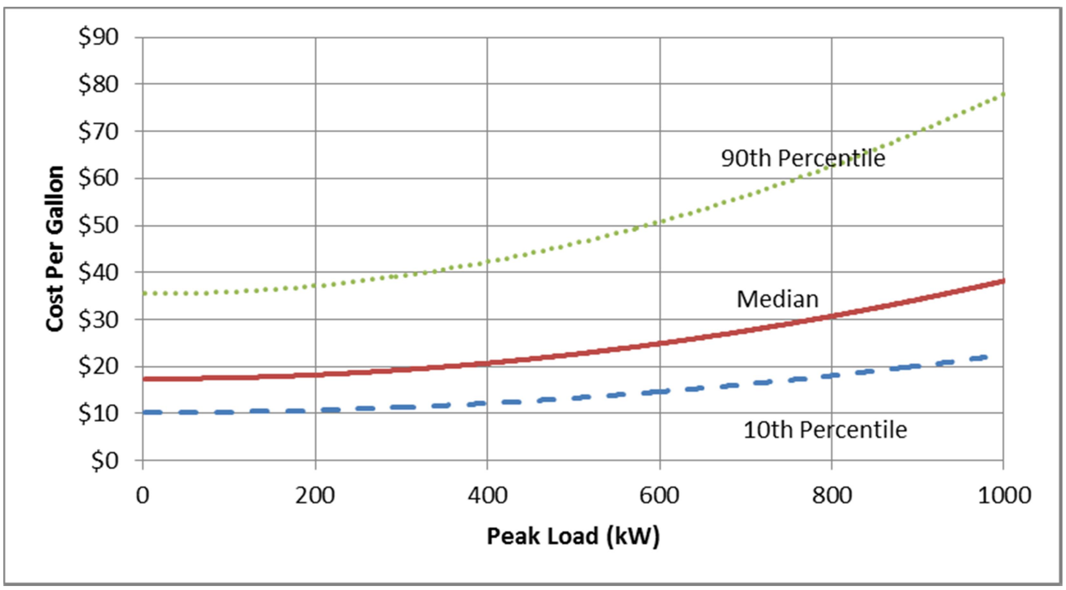

Figure B.18: Squared Risk-Dependent ADP vs Peak Load

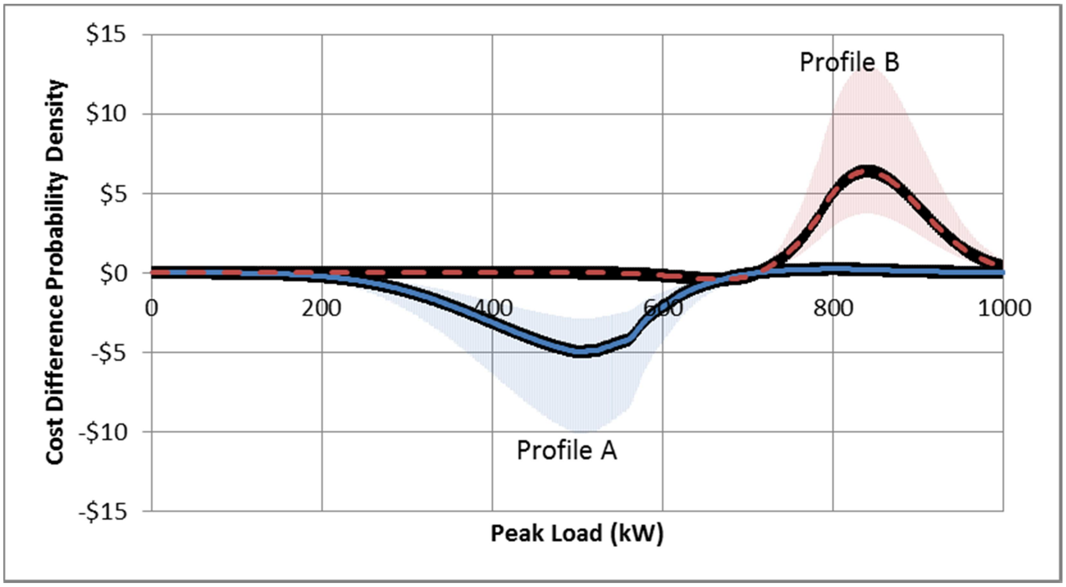

Figure B.19: Squared Cost Difference Probability Density vs Peak Load

Only with the assumption of an exponential relationship, is the 1000 kW alternative preferred across both profiles.

B.18 Correlations

Figure B.20 shows the effect on inputs of assuming a negative correlation between losses due to enemy actions and escort assets. The figure is displayed with the ground forces escort variant, though the general appearance would be unaffected if plotted against the other escort assets. A 90th percentile circle is drawn around the inputs.

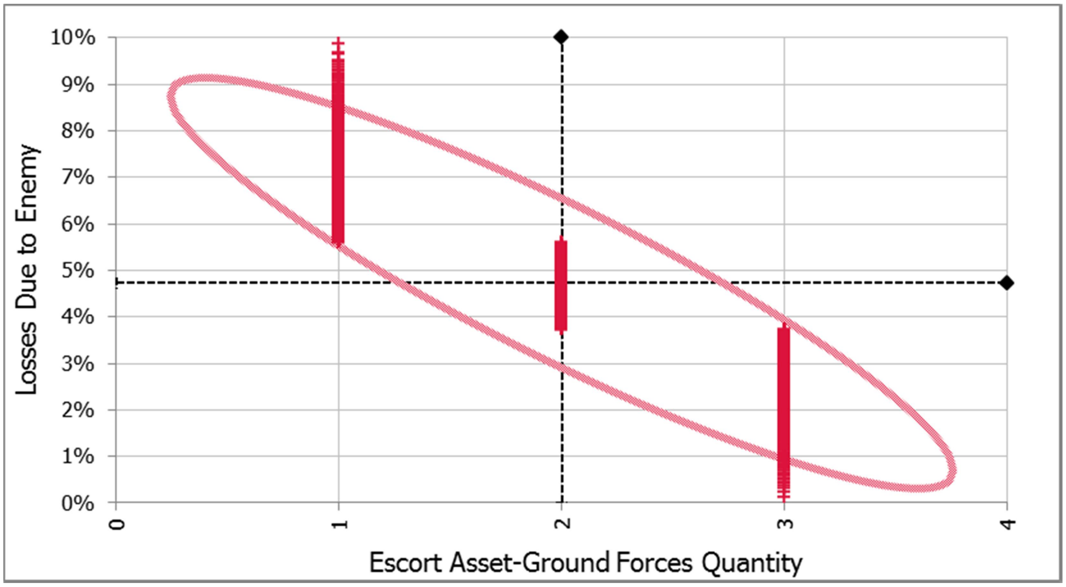

Figure B.20: Correlation Between Losses Due to Enemy and Escort Asset-Ground Forces Quantity

Figure B.21 illustrates the positive correlation between the days to deliver the fuel and the rate of mechanical failure.

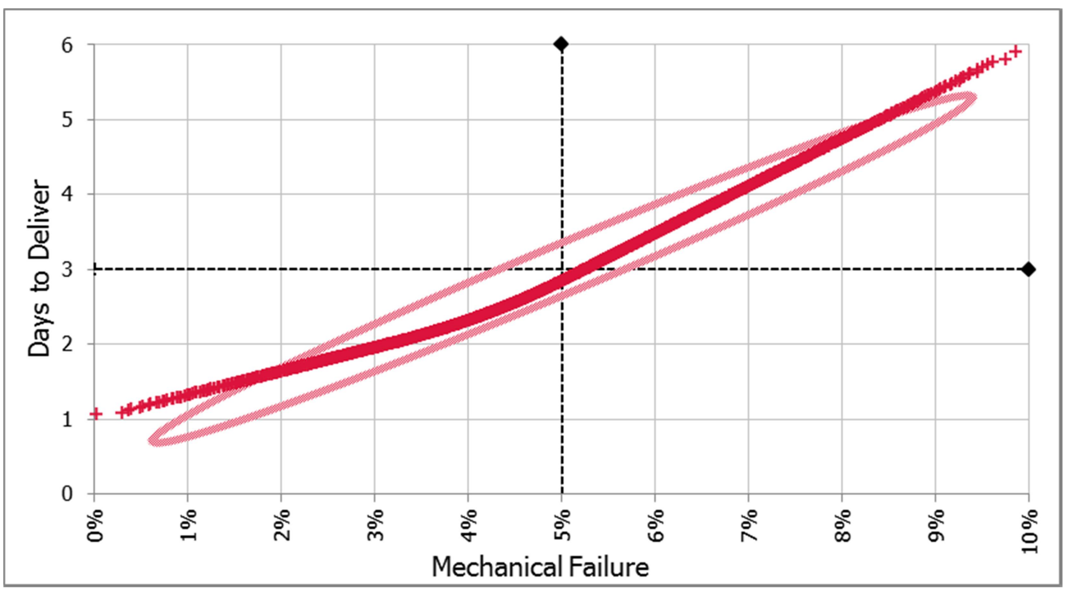

Figure B.21: Correlation Between Days to Deliver and Mechanical Failure

B.19 Escort Asset Loss

Figure B.22 and Figure B.23 are tornado charts for the mean and median cost of fuel. While there are certainly limitations to this sort of analysis given the argument of interconnected inputs proposed in the next section, it is of some value to note the differences in the rank order of input importance for the two statistics.

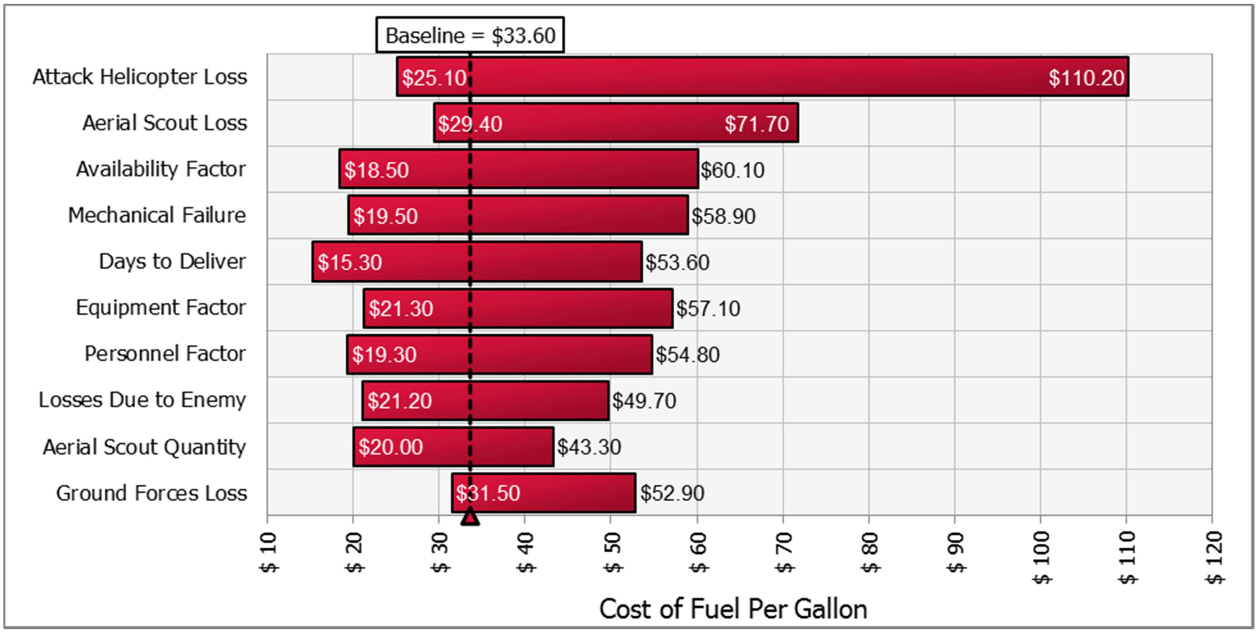

Figure B.22: Tornado Chart of Mean Sensitivity

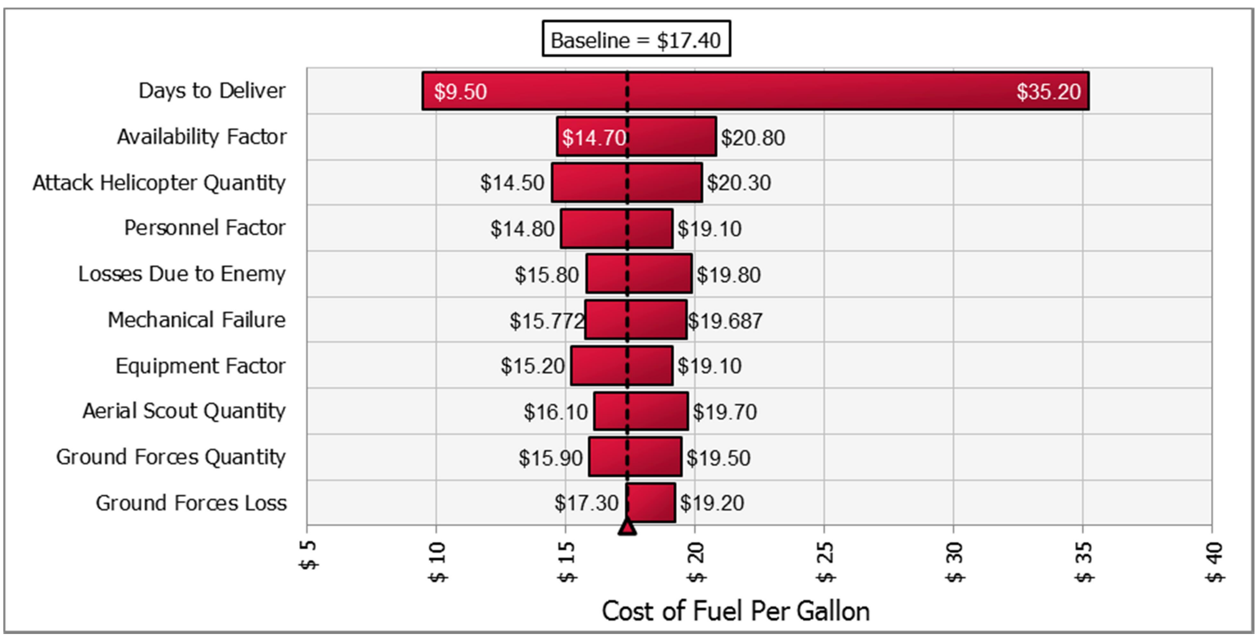

Figure B.23: Tornado Chart of Median Sensitivity

As expected, the mean is much more sensitive to the incorporated uncertainty and its resulting costs, most noticeable in the low probability, high cost of escort asset loss.

B.20 FBCE's Location in the Acquisition Process

Figure B.24 shows a notional layout of the Defense Acquisition Management System framework from initial conception, through development and to initial and full operation [37]. It is a complicated event-based process, where acquisition programs proceed through a series of milestone reviews and other decision points that may authorize entry into a new program phase by satisfying the requirements for each stage as established by various regulations. By the same regulations, FBCE is incorporated into the process outlined in red for Acquisition Category (ACAT) level I and II programs. The interim version of DoDI 5000.02 contains the reasons for the various ACAT designations [63].

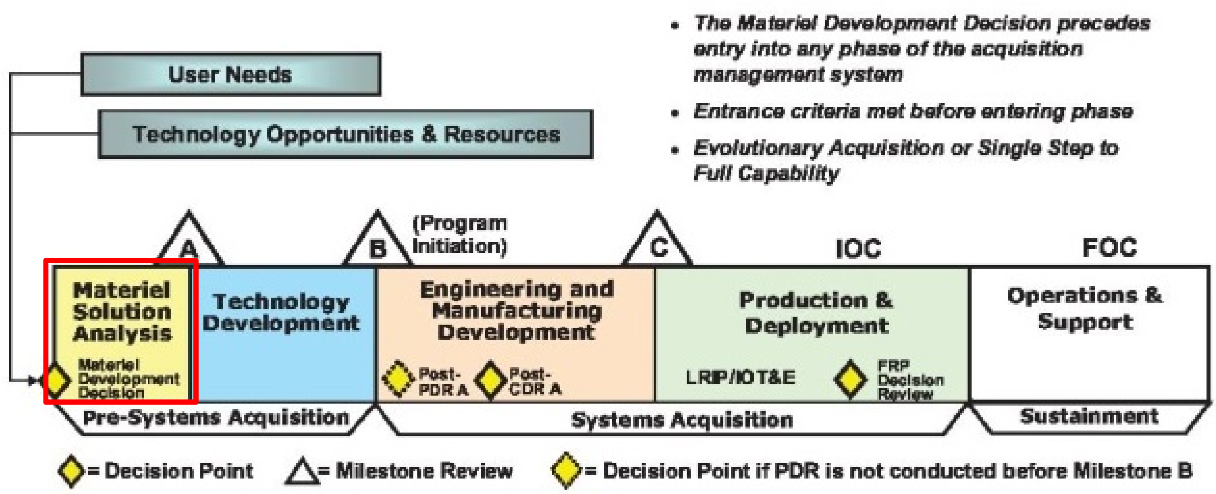

Figure B.24: Defense Acquisition Management System Framework

Basically, user needs and technology opportunities and resources consistent with DoD Strategic Guidance and Joint Operating and Functional Concepts are used to determine a capability gap. An identified capability gap goes to a Materiel Development Decision (MDD), which is a formal entry point into the acquisition process mandatory for all programs. During this phase the Initial Capabilities Document (ICD) and guidance for an Analysis of Alternatives are generated. A successful decision at the Materiel Development Decision leads into a Materiel Solution Analysis (MSA), where the Analysis of Alternatives is conducted. The Analysis of Alternatives assesses potential materiel solutions to satisfy the gap and is the location where FBCE is incorporated. Trying to engage this issue early allows time to choose systems with lower FBCE without impacting other aspects like cost and schedule. However at this point, a lot of uncertainty exists not only in these potential future systems but also their operational scenarios of intended use.

B.21 Acquisition Category Definitions

Table B.9: Description of Acquisition Categories I-III [63]

ACAT	Reason for ACAT Designation	Decision Authority
ACAT I	• MDAP (10 U.S.C. 2430 (Reference (n))) ○ Dollar value for all increments of the program: estimated by the DAE to require an eventual total expenditure for research, development, and test and evaluation (RDT&E) of more than $480 million in Fiscal Year (FY) 2014 constant dollars or, for procurement, of more than $2.79 billion in FY 2014 constant dollars ○ MDA designation • MDA designation as special interest[1]	ACAT ID: DAE or as delegated ACAT IC: Head of the DoD Component or, if delegated, the CAE (not further delegable)
ACAT IA[2, 3]	• MAIS (10 U.S.C. 2445a (Reference(n))): A DoD acquisition program for an Automated Information System[4] (AIS) (either as a product or a service[5]) that is either: ○ Designated by the MDA as a MAIS program; or ○ Estimated to exceed: ▪ $40 million in FY 2014 constant dollars for all expenditures, for all increments, regardless of the appropriation or fund source, directly related to the AIS definition, design, development, and deployment, and incurred in any single fiscal year; or ▪ $165 million in FY 2014 constant dollars for all expenditures, for all increments, regardless of the appropriation or fund source, directly related to the AIS definition, design, development, and deployment, and incurred from the beginning of the Materiel Solution Analysis Phase through deployment at all sites; or ▪ $520 million in FY 2014 constant dollars for all expenditures, for all increments, regardless of the appropriation or fund source, directly related to the AIS definition, design, development, deployment, operations and maintenance, and incurred from the beginning of the Materiel Solution Analysis Phase through sustainment for the estimated useful life of the system. • MDA designation as special interest[1]	ACAT IAM: DAE or as delegated ACAT IAC: Head of the DoD Component or, if delegated, the CAE (not further delegable)
ACAT II	• Does not meet criteria for ACAT I or IA • Major system (10 U.S.C. 2302d (Reference (n))) ○ Dollar value: estimated by the DoD Component Head to require an eventual total expenditure for RDT&E of more than $185 million in FY 2014 constant dollars, or for procurement of more than $835 million in FY 2014 constant dollars ○ MDA designation5 (10 U.S.C. 2302 (Reference (n)))	CAE or the individual designated by the CAE[6]
ACAT III	• Does not meet criteria for ACAT II or above • An AIS program that is not a MAIS program	Designated by the CAE[6]

1. The Special Interest designation is typically based on one or more of the following factors: technological complexity; congressional interest; a large commitment of resources; or the program is critical to the achievement of a capability or set of capabilities, part of a system of systems, or a joint program. Programs that already meet the MDAP and MAIS thresholds cannot be designated as Special Interest.
2. When a MAIS program also meets the definition of an MDAP, the DAE will be the MDA unless delegated to a DoD Component or other official. The DAE will designate the program as either a MAIS or an MDAP, and the Program Manager will manage the program consistent with the designation.
3. The MDA (either the DAE or, if delegated, the DoD Chief Information Officer (CIO) or another designee) will designate MAIS programs as ACAT IAM or ACAT IAC. MAIS programs will not be designated as ACAT II.
4. AIS: A system of computer hardware, computer software, data or telecommunications that performs functions such as collecting, processing, storing, transmitting, and displaying information. Excluded are computer resources, both hardware and software, that are an integral part of a weapon or weapon system; used for highly sensitive classified programs (as determined by the Secretary of Defense); used for other highly sensitive information technology (IT) programs (as determined by the DoD CIO); or determined by the DAE or designee to be better overseen as a non-AIS program (e.g., a program with a low ratio of RDT&E funding to total program acquisition costs or that requires significant hardware development).
5. Acquisitions of services that satisfy or are expected to satisfy the definition of a MAIS in 10 U.S.C. 2445c, Reference (n), will comply with this instruction. All other acquisitions of services will comply with Enclosure 9 of DoD Instruction 5000.02 (Reference (b)).
6. As delegated by the Secretary of Defense or Secretary of the Military Department.

B.22 Additional Conclusions and Future Work

Incorporating the first two dramatically altered the average ADP depending on the assumed probability of loss. For example, a 0.1% escort loss rate assumption increased the average ADP by around 37% from $9.75 to $13.40 and the calculated casualty rate of 3.0E-5 per gallon might be critical to a decision maker as it highlights another consequence of fuel demand.

Developing significance across greater breadth is also crucial to translating large burdened fuel costs in a given scenario to relevance at acquisition decisions. Part of the scenario exploration will necessitate expanding the framework to model the costs of joint operations. Modern warfare relies on the services working together to meet DoD and national objectives. Given this and the current and forecasted financial pressure on the DoD, future operations will likely depend even more on joint action. The framework needs to be able to create scenarios that reflect this expectation.

B.23 Additional Policy Implications

While mentioned in the previous section, expanding any FBCE framework to more properly represent the "jointness" of modern operations will be difficult. The various services have different logistic systems that result in different critical assumptions and FBCE methods. Ultimately, this has led to a general disagreement on the current value of this metric and, accordingly, the importance of supporting future work to develop it. While DoD wide organizations, such as OEPP, must carefully balance respecting service differences and pushing for standardization, these organizations may be the only ones properly positioned to reignite the FBCE discussion at a joint level. This would require a combination of fundamental improvements to the FBCE concept and method, and a direct address of service attitudes that seem to be either avoiding FBCE all together or creating methods that undermine its potential value. Until these are addressed, FBCE is unlikely to be of any value to the DoD, remaining only relevant in select offices for very specific purposes.

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Appendix C: Additional Analysis

C.1 OEPP's FBCF Calculator

C.1.1 Introduction

Our work became by examining some of the existing FBCE modeling. In addition to those mentioned in Chapter 1 and Appendices A and B (LIA's, NPS's, and DASA-CE's), we investigated OEPP's FBCF Calculator. This spreadsheet based tool was the first application attempt found and the starting point for many of the individual Services. It was made at a time that pre-dates the FBCE terminology when FBCF was part of total ownership cost and broken by Operational Tempo (OPTEMPO). The calculator accounts for interdiction losses and fuel consumed during delivery. A detailed list of assumptions and the methodology used can be found in the tool's documentation [1]. An example of the input interface is shown below in Figure C.1.

Symbols	Parameter Name	Units	Value	5%	95%
CR_V	Fuel Consumption Rate by 1 delivery Vehicle	gal/hour	1,600	1,550	1,650
CR_E	Fuel Consumption Rate by 1 Escort vehicle	gal/hour	0	0	0
CR_A	Fuel Consumption Rate by 1 escort Aircraft	gal/hour	800	750	850
T	Number of hours to deliver fuel (round-trip)	hours	7.0	6.5	7.5
A	Multiplier to keep convoy fuel flowing	#	1.0	1.0	1.0
Q	Capacity of one delivery vehicle	gal	29,680	29,650	29,710
TC_V	Total Life-Cycle Cost (LCC) of 1 delivery Vehicle (Peacetime estimate)	$	$150,000,000	$145,000,000	$155,000,000
PC_V	Procurement Cost fraction of delivery Vehicle's LCC	#	0.33	0.30	0.36
OS_V	O&S cost fraction of delivery Vehicle's LCC	#	0.60	0.55	0.65
P	Probability of an interdiction event during a delivery mission	#	0.040	0.035	0.045
λ	Number of delivery vehicles Lost during the interdiction	#	0.00	0	0
LM_V	LCC Multiplier to account for surge usage of delivery Vehicle	#	2.0	1.5	2.5
M_μ	Average age of a delivery vehicle	hours	30,000	25,000	35,000
M_V	Number of hours 1 delivery Vehicle will be used during its lifetime	hours	50,000	45,000	55,000
TC_E	Total life-cycle Cost of 1 Escort vehicle (Peacetime estimate)	$	$1,000	$1,000	$1,000
LM_E	LCC Multiplier to account for surge usage of Escort vehicle	#	0.0	0.0	0.0
ER_E	Escort Ratio (number of delivery vehicles per Escort vehicle)	#	1,000,000	1,000,000	1,000,000
M_E	Number of hours 1 Escort vehicle will be used in its lifetime	hours	6,000	6,000	6,000
TC_A	Total life-cycle Cost of 1 escort Aircraft (Peacetime estimate)	$	$120,000,000	$115,000,000	$125,000,000
LM_A	LCC Multiplier to account for surge usage of escort Aircraft	#	2.5	2.0	3.0
ER_A	Aircraft Escort Ratio (number of delivery vehicles per escort aircraft)	#	0.500	0.450	0.550
M_A	Number of hours 1 escort Aircraft will operate during its lifetime	hours	30,000	25,000	35,000

Symbols	Price Element Name (All entries are in $/gal)	Operational	Steady-State	5%	95%
SP_1, FP_1	Commodity Price of Fuel	$3.17	$3.17	$3.17	$3.17
FP_2	Primary Fuel Delivery Asset O&S Price (Foundational Activity)		$2.43	$2.40	$2.45
FP_3	Depreciation Price of Primary Fuel Delivery Assets (Foundational Activity)		$0.45	$0.44	$0.46
SP_4	Direct Fuel Infrastructure O&S and Recapitalization Price (Surge)	$0.02		$0.01	$0.03
FP_4	Direct Fuel Infrastructure O&S and Recapitalization Price (Foundational Activity)		$0.02	$0.01	$0.03
SP_5	Indirect Fuel Infrastructure O&S Price (Surge)	$0.02		$0.01	$0.03
FP_5	Indirect Fuel Infrastructure O&S Price (Foundational Activity)		$0.02	$0.01	$0.03
SP_6	Environmental Price (Surge)	$0.10		$0.10	$0.10
FP_6	Environmental Price (Foundational Activity)		$0.10	$0.10	$0.10
FP_7	Other Service & Platform Delivery Specific Prices (Foundational Activity)		$20.50	$20.00	$21.00

Symbols	Scenario Parameter Name (units)	Operational	Steady-State	5%	95%
OR	OPTEMPO Ratio (#)	0.50		0.45	0.55
P_S	System Proportion (Surge) (#)	0.750		0.700	0.800
P_F	System Proportion (Foundational Activity) (#)		0.750	0.7	0.800
D_S	Total fuel Demanded at final delivery location (Surge) (gal/hour)	27,500		20,000	35,000
D_F	Total fuel Demanded at final delivery location (Foundational Activity) (gal/hour)		27,500	20,000	35,000
N_S	Number of vehicles located at final delivery location (Surge) (#)	12		10	14
NF	Number of vehicles located at final delivery location (Foundational Activity) (#)		12	10	14

Figure C.1: Figure of Calculator Input Screen

The rest of this section contains an overview of OEPP's FBCF Calculator method and attempts to make overcome its most apparent limitations.

C.1.2 Methodology Overview

The calculator determines a separate ADP for two OPTEMPOs, foundational and surge. Each ADP is the summation of the following seven price elements:

1. Commodity Price of Fuel
2. Primary Fuel Delivery Asset O&S Price
3. Depreciation Price of Primary Fuel Delivery Assets
4. Direct Fuel Infrastructure O&S and Recapitalization Price
5. Indirect Fuel Infrastructure O&S Price
6. Environmental Price
7. Other Service & Platform Delivery Specific Prices

The calculator assumes all of these fourteen price elements are available or can be computed through traditional cost analysis techniques except for Surge Price Elements 2, 3, and 7 (SP_2, SP_3, and SP_7). To determine these price elements, the user must specify the average, 5^{th}, and 95^{th} percentile of the parameters listed in Table C.1.

Table C.1: Input Parameters for SP_2, SP_3, and SP_7

Parameter	Symbol	Units
Fuel Consumption Rate by 1 delivery Vehicle	CR_V	gal/day
Fuel Consumption Rate by 1 Escort vehicle	CR_E	gal/day
Fuel Consumption Rate by 1 escort Aircraft	CR_A	gal/day
Number of days to deliver fuel (round-trip)	T	days
Multiplier to keep convoy fuel flowing	A	#
Capacity of one delivery vehicle	Q	gal
Total Life-Cycle Cost (LCC) of 1 delivery Vehicle (Peacetime estimate)	TC_V	$
Procurement Cost fraction of delivery Vehicle LCC	PC_V	#
O&S cost fraction of delivery Vehicle LCC	OS_V	#
Probability of an interdiction event during a delivery	P	#
Number of delivery vehicles Lost during the interdiction	λ	#
LCC Multiplier to account for accelerated surge usage of delivery Vehicle	LM_V	#
Average age of a delivery vehicle	Mμ	days
Number of days 1 delivery Vehicle will be used during its lifetime	M_V	days
Total life-cycle Cost of 1 Escort vehicle	TC_E	$
LCC Multiplier to account for surge usage of Escort vehicle	LM_E	#
Escort Ratio (delivery vehicles per Escort vehicle)	ER_E	#
Number of days 1 Escort vehicle will be used in its lifetime	M_E	days
Total life-cycle Cost of 1 escort Aircraft	TC_A	$
LCC Multiplier to account for surge usage of escort Aircraft	LM_A	#
Aircraft Escort Ratio (delivery vehicles per escort aircraft)	ER_A	#
Number of days 1 escort Aircraft will operate during its lifetime	M_A	days

Intermediate steps can be found in the documentation. The final equations for SP_2, SP_3, and SP_7 are displayed below in Equation C.1**Error! Reference source not found.**, Equation C.2, and Equation C.3.

$$SP_2 = \frac{\left(T * N_V * \dfrac{OS_V * LM_V * TC_V}{M_V}\right)}{D_S} \qquad C.1$$

$$SP_3 = \frac{\left(T * N_V * \dfrac{PC_V * TC_V}{M_V}\right) + \left[P * \lambda * \left(1 - \dfrac{M_\mu}{M_V}\right) * PC_V * TC_V\right]}{D_S} \qquad C.2$$

$$SP_7 = \frac{T * \left\{ \left[N_E * \left(\frac{LM_E * TC_E}{M_E} \right) \right] + \left[N_A * \frac{(LM_A * TC_A)}{M_A} \right] \right\}}{D_S} \qquad C.3$$

The calculator then determines the surge and foundational ADP by summing the 7 price elements for each. It then computes an average OPTEMPO ADP by assuming a weighting ratio. The weighting ratio is calculated through additional user inputs. FBCF is calculated by multiplying ADP by the assumed demand. In the end, the calculator generates a foundational, surge, and average ADP and FBCF.

As drafted, the process was an important starting point for application methods but had several limitations. First, the calculator puts a large burden on users. It assumes 11 of the 14 price elements are readily available or producible from readily available information and requires 140+ inputs to generate the other three. Second, the calculator requires highly confident input bounds. The six examples available produce reasonably bounded results (e.g., the output tables and figures for the "Interdicted Air, Ex 1" are shown below) [2]–[7]. However, slight expansion on the bounds of some inputs results in explosive distributions that expand into infeasible and/or non-positive results. This is partly because the calculator assumes all normal distributions. Third, the calculator gives decision makers no assistance in interpreting the results. It doesn't generate any formal sensitivity analysis or otherwise inform those looking at the results which assumptions or inputs are most critical to the results.

Symbol	Name	Units	5%	Mean	95%
SP_2	**Surge Price Element 2 (SP2), Delivery Asset O&S Price:**	$/gal	$2.19	$4.09	$5.99
SP_3	**Surge Price Element 3 (SP3), Depreciation Price of Fuel Delivery Assets:**	$/gal	$0.68	$1.13	$1.58
SP_7	**Surge Price Element 7 (SP7), Other Prices:**	$/gal	$12.10	$24.33	$36.56
Intermediate Computed Values:					
L	Fuel Loaded out from DESC terminal	gal	66,349	116,799	167,248
α	Additional amount of fuel loaded out due to interdiction	gal	0	0	0
N_V	Number of delivery Vehicles needed to deliver fuel load-out	#	3	4	6
N_E	Number of Escort vehicles needed to protect delivery vehicles	#	1	1	1
N_A	Number of escort Aircraft needed to protect delivery vehicles	#	5	9	13
C_V	Total Fuel Consumed by delivery Vehicles	gal	27,605	50,039	72,474
C_E	Total Fuel Consumed by Escort vehicles	gal	0	0	0
C_A	Total Fuel Consumed by escort Aircraft	gal	26,812	53,199	79,586

Figure C.2: Calculator Report

Price Element:		E1	E2	E3	E4	E5	E6	E7
(All Price Element units are $/gal)		**Commodity Price of Fuel (DESC)**	**Fuel Delivery O&S Price**	**Depreciation Price of Fuel Delivery Assets**	**Direct Fuel Infrastructure O&S Price**	**Indirect Fuel Infrastructure O&S Price**	**Environmental Price**	**Other Prices (Force Prot. etc.)**
Surge Scenario Prices:		SP_1	SP_2	SP_3	SP_4	SP_5	SP_6	SP_7
	5%	$3.17	$2.19	$0.68	$0.01	$0.01	$0.10	$12.10
	Mean	$3.17	$4.09	$1.13	$0.02	$0.02	$0.10	$24.33
	95%	$3.17	$5.99	$1.58	$0.03	$0.03	$0.10	$36.56
Foundational Scenario Prices:		FP_1	FP_2	FP_3	FP_4	FP_5	FP_6	FP_7
	5%	$3.17	$2.40	$0.44	$0.01	$0.01	$0.10	$19.99
	Mean	$3.17	$2.42	$0.45	$0.02	$0.02	$0.10	$20.51
	95%	$3.17	$2.45	$0.46	$0.03	$0.03	$0.10	$21.02
Scenario Parameters:		**OPTEMPO Ratio (*OR*)**	**Surge Proportion (P_S)**	**Foundational Proportion (P_F)**	**S Demand (D_S) (gal/hour)**	**F Demand (*DF*) (gal/hour)**	**Number of Vehicles in S Unit (N_S)**	**Number of Vehicles in F Unit (N_F)**
	5%	45%	70.1%	69.9%	20,250	19,398	10	10
	Mean	50%	75.0%	74.9%	27,571	27,257	12	12
	95%	55%	79.8%	80.0%	34,892	35,116	14	14
Results:		**Surge Activities**		**Foundational Activities**		**OPTEMPO Averaged (per vehicle)**		
		ADP_S	***$FBCF_S$***	***ADP_F***	***$FBCF_F$***	***ADP***	***FBCF***	**Demand**
		$/gal	**$/hour**	**$/gal**	**$/hour**	**$/gal**	**$/hour**	**gal/hour**
	5%	$18.95	$27,610	$26.17	$30,215	$22.80	$35,095	1,316
	Mean	$32.86	$56,792	$26.69	$46,131	$29.78	$51,494	1,733
	95%	$46.76	$85,973	$27.21	$62,048	$36.75	$67,893	2,150

Figure C.3: FBCF Report

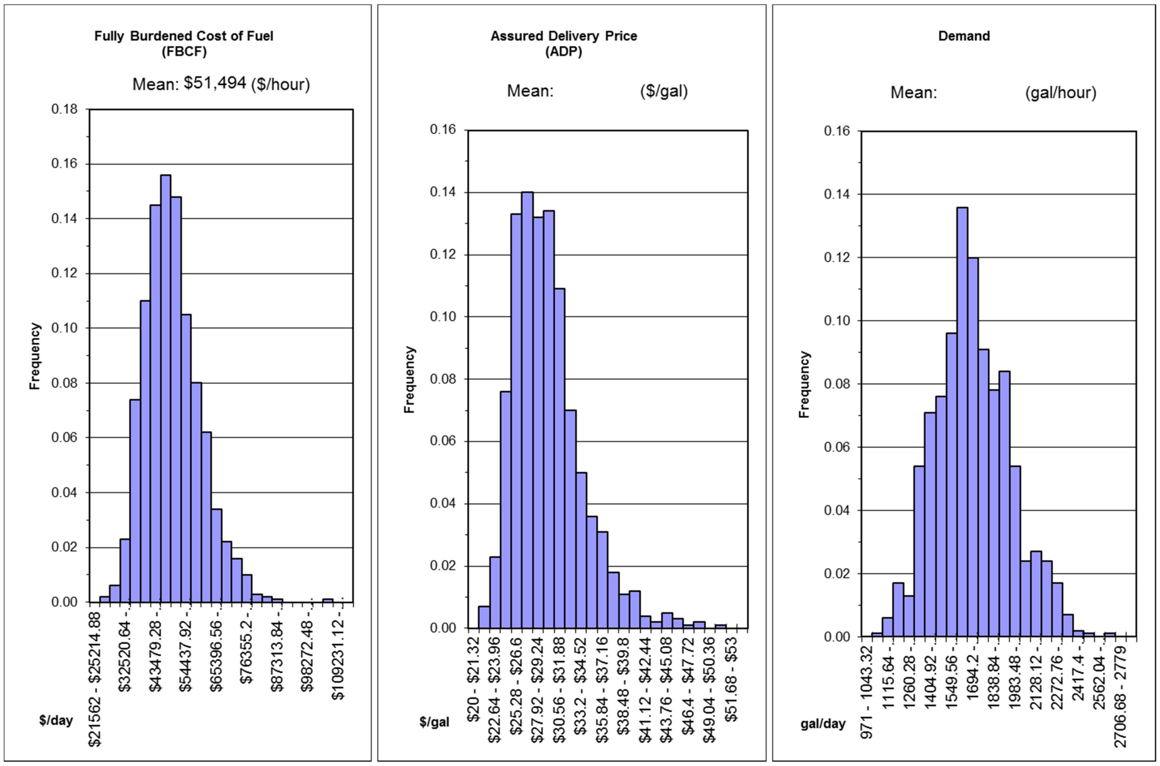

Figure C.4: Histogram Output

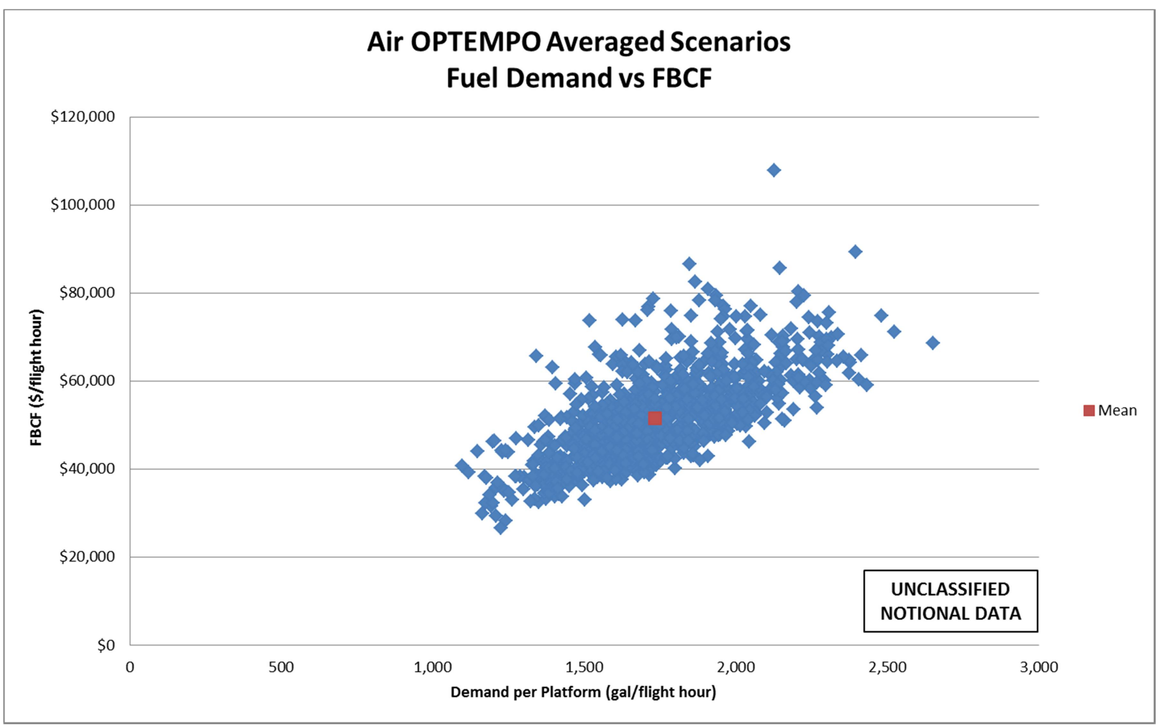

Figure C.5: FBCF Plot

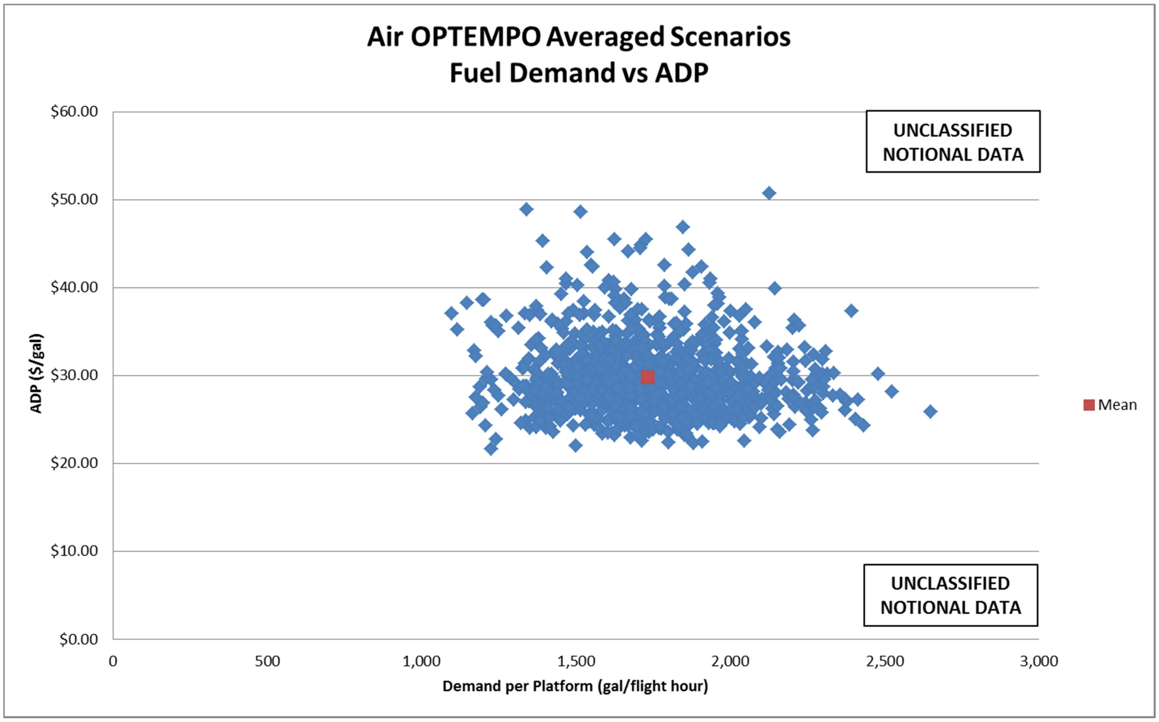

Figure C.6: ADP Plot

C.1.3 Additional Work

Some time was spent remaking this calculator. Below is a list of work done:

1. More descriptive ways to calculate the other price elements were created.
2. The modeling was remade with distributions more appropriate to the various parameters and overall intent. This removed the possibility of negative results.
3. Sensitivity reports were added to the automatically generated outputs.
4. The number of required inputs was reduced by simplifying the equations and being more selective with the chosen distributions.

Ultimately, though it was eventually abandoned, the lessons learned from this work served as a starting point for our new framework.

C.2 Unused Guadalcanal Analysis

C.2.1 Excluded Resupply Runs

Table C.2 shows the resupply runs excluded from the analysis in Chapter 3. They were excluded either because of incomplete information or the use of sea plane carriers. With some additional research to find the missing information and estimate the fuel consumption of World War II Japanese sea plane carriers, Chapter 3 analysis could be updated to include this data.

Table C.2: Excluded Resupply Runs between 4 September and 12 October [8]
Note: DD = Destroyer, CL = light cruiser, SP = sea plane carrier

Date in 1942	Resupplying Vessels	Escorting Vessels	Soldiers Transported	Average Soldiers Per Ship	Other Supplies
Oct 1-2	4 DD	None	Unknown	NA	None
Oct 2-3	5 DD	None	Unknown	NA	None
Oct 3-4	2 DD & 1 SP	None	330	165.0	9 artillery (4 15cm howitzers)
Oct 6-7	6 DD & 1 SP	1 CL	600	85.7	4 anti-tank, 4 regimental guns
Oct 8-9	1 SP	None	180	180.0	6 AA guns, 2 10cm howitzers, 1 tractor
Oct 11-12	2 SP	None	280	140.0	4 15cm how, 2 field guns, 1 AA gun

C.2.2 Other Supplies Conversion

The analysis shown in Chapter 3 excluded supplies delivered by both resupply options. Initial analysis found the comparison of resupply options largely insensitive to their inclusion. In case there is a desire to include these supplies and remake the figures, this section contains a summary of our findings.

In World War II, the most common Japanese tank and field gun were the Type 97 Chi-Ha medium tank and Type 38 75 mm field gun. These systems had weights of around 15 and 1.5 tons, respectively. For the Tokyo Express option, assume the 5-6 September run with the unknown quantity of provisions carried the average transported by the runs with known amounts (i.e., 18 tons), the ammunition included on the 5-6 October run was small enough to ignore, and the mortars included on the 8-9 October run were 1/20th the weight of the Type 38 field gun. Assuming a soldier equivalent weight of 100 kg, the median for the fitted soldiers per resupply destroyer distribution increases from 114 to 129.

Along with the soldiers, the transport vessel resupply option on 13-14 October delivered one battery each of 10 cm and 15 cm howitzers, a battalion of antiaircraft guns, a tank company, and stocks of ammunition and provisions. Assume the howitzer batteries each contain 6 guns, the 10 cm howitzer, 15 cm howitzer and antiaircraft guns weight approximately the same as the Type 38 field gun, a battalion consists of 4 batteries, the tanks were Type 97, the company consisted of 14 tanks, and the quantity of ammunition and provisions carried were small enough to ignore. Assuming the same soldier equivalent weight of 100 kg, results in the 13-14 October transport vessel option delivering 7,020 soldiers instead of 4,500 or increasing the median from 750 per transport vessel to 1,170.

Therefore as would be expected, including other supplies creates additional preference for the transport vessel option as it increases its estimated capacity by 56% while only increasing the Tokyo Express option's by around 13%. Carrying the impacts of these assumptions through the rest of the analysis in Chapter 3 impacts the metrics but does not result in dominant preference for the transport vessel option (i.e., there are still reasons why a decision maker may prefer the Tokyo Express option). Accordingly, because of the number of assumptions required to get to these results, other supplies were excluded from the results in that chapter.

C.2.3 Scale Liberty Ship Consumption for Tonnage

Information on the fuel consumption of the Japanese transport ships used during those resupply missions during the Guadalcanal Campaign were not found. The Liberty ship's fuel consumption was used as an available substitute. As noted in that chapter, compared to the transport vessels used, the Liberty ship had a 6-11% higher deadweight tonnage (DWT) and 4-15% higher gross registered tonnage (GRT). If a DWT or GRT to fuel consumption relationship were found, the Liberty ship fuel consumption estimate could be more closely scaled to the Japanese vessels.

C.3 References

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