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OPTIMIZING COST AND PERFORMANCE OF INFRASTRUCTURE ALTERNATIVES AT CONTINGENCY BASES IN A HUB-AND-SPOKE NETWORK

THESIS

Kyle J. Rodriguez, Captain, USAF

AFIT-ENV-MS-21-M-263

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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THESIS

Presented to the Faculty

Department of Engineering and Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

Kyle J. Rodriguez, BS

Captain, USAF

March 2021

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OPTIMIZING COST AND PERFORMANCE OF INFRASTRUCTURE ALTERNATIVES AT CONTINGENCY BASES IN A HUB-AND-SPOKE NETWORK

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AFIT-ENY-MS-21-M-263

Abstract

Military operations are conducted worldwide, from the mountainous regions of Afghanistan to Somalia's dry and arid plains. A substantial amount of resources and funding are required to construct and sustain these large-scale military operations. In 2010, there were a reported 700 U.S. and coalition military bases throughout Iraq and Afghanistan, with a construction value of nearly $6.2 billion. Contingency bases are generally geographically separated from larger, enduring, main operating bases and have minimal access to an established infrastructure grid in a hostile environment. The absence of a usable infrastructure grid at these sites drives the need for the contingency base to produce essential functions such as power, potable water, and waste management with internal infrastructure assets. Current combinations of infrastructure assets deployed at these contingency bases deliver the necessary outputs for sustainment. Still, they are accompanied by high costs and resupply requirements that produce a significant logistical burden on the support network. An extensive logistics supply chain is continuously working to deliver the varying resources required to sustain contingency bases within a network. The two primary resources in constant demand are fuel and potable water. These two crucial resources accounted for nearly 70% of the total tonnage transported by convoys to contingency bases. With the current high-cost state of modern battlespaces and the increasing near-peer threats of opposing military forces, there is a need for contingency bases to become more self-sufficient, agile, easy to construct and maintain with alternative combinations that reduce the overall required resources for sustainment.

Accordingly, this research aims to develop a model capable of selecting optimal infrastructure alternative combinations that minimize the overall resource requirement at multiple contingency bases within a hub-and-spoke network. The objectives of this research are as follows: (1) examine current literature encompassing infrastructure alternative optimization, (2) identify and quantify tradeoffs between infrastructure alternative cost versus performance, and (3) develop a model that is capable of optimizing infrastructure alternative combinations at the base level to minimize overall costs and resource requirements within a hub-and-spoke network. A case study with theoretical contingency bases in a hub-and-spoke network is developed to demonstrate the model's capabilities. The results signify the model successfully reduces the costs and resources required to sustain a contingency base. This study's impacts will enable planners to construct more efficient and sustainable contingency bases across current and future areas of operation.

Acknowledgments

First, I would like to thank my wife, for her unwavering support and patience throughout my military career and this life we lead together. I could not have come as far as I have or push as far as I will go without you, thank you. Second, I would like to thank my academic advisor, Lt Col Schuldt, for mentoring, driving, and supporting me throughout my time at AFIT. I would not have been able to accomplish this research endeavor without your guidance. Next, I would like to thank my committee members and ENV faculty that made this research possible. Lastly, to all the friends, family, and classmates, thank you for your support in each of your own ways. It means the world to me that I have been given such a great support system.

Kyle Joseph Rodriguez

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OPTIMIZING COST AND PERFORMANCE OF INFRASTRUCTURE ALTERNATIVES AT CONTINGENCY BASES IN A HUB-AND-SPOKE NETWORK

I. Introduction

Background

U.S. military operations are conducted worldwide, which require logistical support to sustain the military presence and varying missions. Since September 2001, operations to combat terrorism have been highlighted in the Middle East, Africa, South America, and Asia. However, the next generation of conflicts is projected to transition from terrorism to near-peer threats (USOSD 2018). The changing threats require the expansion and sustainment of military operations across the globe. These varying, extensive military operations require an equally large and complex logistical network to support the personnel and equipment currently deployed in the area of operations. For example, there were a reported 700 U.S. and coalition military bases throughout Iraq and Afghanistan in 2010, with a construction value of nearly $6.2 billion (Noblis 2010). A hub-and-spoke network (Figure 1) is one example of a military logistics network that includes large enduring main operating bases surrounded by smaller contingency bases with transportation routes that connect them (Skipper 2002).

The main operating bases are responsible for resupplying contingency bases with essential infrastructure resources to sustain operations along varying transportation routes. Generally, contingency bases are not connected to an established infrastructure grid due to resource incompatibility, substandard reliability, and security vulnerabilities

(Putnam 2012). Due to no or limited access to an established infrastructure grid, contingency bases are not self-sustaining and require constant and costly resupply of sustainment resources. Delivery of fuel and potable water and removal of solid and liquid waste are the primary resources coming into or leaving a contingency base. Contingency bases located in Kuwait and Iraq in 2008 required 125 fuel trucks a day to sustain their respective missions. 70 percent of those 125 trucks were transporting fuel and potable to contingency bases (GAO 2009). Furthermore, at the single contingency base scale, a 600-person base required more than 22 trucks per day to transfer fuel and water on base while disposing of generated waste off base (Noblis 2010).

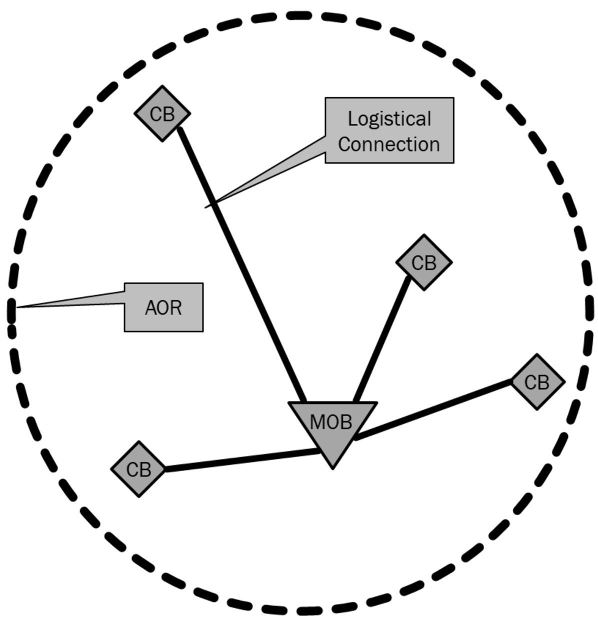


Figure 1: Hub-and-spoke network example, adapted from Skipper et al. 2016.

Problem Statement

Contingency bases utilize combinations of infrastructure assets to meet essential daily requirements and sustain base personnel. These requirements are often met with inefficient combinations of technologies that require high capital, initial setup, and maintenance costs. The base level's extensive resource requirements also produce the need for continuous resupply by convoy at varying transportation costs and distances at the network level. Due to high daily sustainment requirements and increasing logistical supply costs, there is a pressing need for the military to optimize the infrastructure alternative combinations at the base level to reduce overall costs of base sustainment and resupply requirements. This study strives to quantify and optimize the tradeoffs between infrastructure alternatives to minimize the sustainment requirements and costs at the base level within a military supply network to address this pressing research need.

Research Objectives

The objectives of this thesis research are summarized as follows:

1. Execute a comprehensive review of the current body of literature pertaining to the sustainability practices, techniques, and optimization methods related to contingency base infrastructure.
2. Identify and quantify tradeoffs between infrastructure alternative performance and alternative costs of deployment, sustainment, and resupply at the contingency base level.
3. Develop an optimization model capable of balancing tradeoffs between

infrastructure alternative performance and economic performance at multiple contingency bases within a military logistical supply network.

Significance

This research presents an optimization model capable of balancing trade-offs between alternative infrastructure at the base level within a hub-and-spoke network. The optimizations results represent the most efficient infrastructure combinations while taking into account the military planners' preferences to minimize cost and infrastructure alternative performance. A case study is performed on a designed logistical network and associated contingency bases to highlight the capabilities possible by this model. This model's optimization techniques are expected to support military planners in the critical task of selecting more efficient infrastructure alternative combinations for deployment at contingency bases that reduce the demand for resupply and reduce the cost of sustainment at the hub-and-spoke network level.

The Way Forward

This research will follow a traditional thesis approach to solve the aforementioned objectives. Chapter two will synthesize and analyze the current body of literature surrounding the areas of interest for this research. These areas of interest are (1) optimization of infrastructure alternatives at contingency bases and remote communities, (2) optimization techniques at the contingency base level, and (3) contingency base characteristics and planning factors.

Chapter three gathers and organizes the varying infrastructure alternatives and associated data considered in this study. This data includes the description, quantity, daily resource usage, and costs of each infrastructure alternative. Next, the cost metric, performance metric, decision variables, and objective function are developed and described.

Chapter four presents and analyzes the optimization model results using a realistic but hypothetical case study. The case study involves the development of a hub-and-spoke network with contingency bases having varied characteristics. The results are analyzed at the infrastructure combination level, the contingency base level, and the network level to illustrate the model's capabilities to optimize cost and performance variables according to military planners' preferences.

Finally, chapter five will summarize the key findings, research contributions, and research significance. Next, the limitations of this research will be discussed. Chapter five will conclude with recommendations for future research in this area of study.

II. Literature Review

Introduction

This chapter summarizes the current literature that is related to this research. The first section starts by synthesizing studies that focus on sustainability techniques at remote communities and military bases. The next section covers important planning factors and characteristics of contingency bases that are important to the model formulation. The third section highlights the literature gap between the aforementioned areas of literature.

Infrastructure Alternative Optimization Techniques

There are many approaches in the literature to solve optimization problems with objective functions, constraints, and decision variables based on the data, metrics, and indices required. Specific to this research, the literature revolving around the optimization of alternative selection at contingency bases is of interest. This literature review investigates the optimization of alternatives at the component level, base level, and network level. It is crucial to examine these three levels of detail because they illustrate varying techniques that can be applied to select optimal combinations of alternatives to achieve specific results.

At the component level of optimization, Abdallah and El-Rayes (2016) developed a multiobjective optimization model that maximized the sustainability of an existing building by comparing trade-offs between three infrastructure objectives. Those objectives were to minimize negative environmental impact, minimize upgrade costs, and maximize points on the Leadership in Energy and Environmental Design (LEED) rating system. A list of infrastructure alternatives such as light fixtures, HVAC equipment, urinals, and solar panels was considered for each requirement. A multiobjective optimization model selected different alternatives within each requirement, producing varying optimal output scenarios. The selected alternatives produced a score in the three aforementioned objectives. This study's results highlighted the capabilities of the model to optimally select building upgrades in the pursuit of achieving green certification and promoting cost-effective green upgrade alternatives in existing buildings.

The next four studies focus on the optimization of infrastructure alternatives at the base level. Filer et al. (2019, 2020) developed a novel model that selected combinations of infrastructure alternatives that meet the overall base planning factors, such as fuel, power, potable water, and waste reduction. The alternative combinations were then compared to the output scenarios to find optimal solutions among tradeoffs between cost and environmental impact over varying time frames. This model accounted for the site characteristics such as base population, distance from main operating base, environment, and varying costs associated with the purchase, transportation, and sustainment of alternatives. Filer et al.'s research efforts provide a baseline for the varying type of objectives, constraints, and infrastructure alternative options available for consideration in the development of this researcher's model.

Another study was performed on renewable energy technologies for remote communities in northern Canada (Arriaga et al. 2012). The research focused on reducing the fuel dependency on electricity generation at remote communities by modeling the implementation of renewable energy technologies such as windmills, battery banks, and or solar arrays. Modeling accounted for the community's electrical load demand, estimated energy resources, and infrastructure alternative cost (procurement, setup, and operations and maintenance). This research highlighted that wind technologies have the potential for significant energy output advantage over solar arrays due to estimated climate data. However, solar array technology has smaller installation, operations, and maintenance costs than wind infrastructure alternatives. These technologies have were found to have viable break-even potential in costs despite rising fuel prices.

Another approach to optimizing infrastructure alternatives at the base level utilizes volumetric accounting to minimize investment and logistical resource consumption (Putnam et al. 2016). This study utilizes volumetric resource accounting to develop a decision-support framework to help planners select infrastructure alternatives to reduce the overall costs of sustaining a contingency base. The variables requiring logistical transportation on to the base are fuel and potable. The variables requiring logistical transportation off the base are solid and liquid waste generated by daily operations. Deployment costs and resource utilization of infrastructure alternatives are then analyzed to show tradeoffs between the reduction potential of varying infrastructure combinations. This framework is capable of optimally selecting varying infrastructure combinations to meet varying needs at different contingency bases. This study indicates that utilization of the decision-support framework can reduce the resources required at a base for daily sustainment.

Researchers have also focused their research on optimizing specific categories at the base level, such as facility systems, water treatment, water recycling, and power generation alternatives. Cave et al. (2011) proposed a lean approach to reduce contingency base dependency on the logistical supply chain by targeting specific infrastructure categories. The two categories of interest in this study were facilities and water treatment and recycling. Within the first category of facilities, the authors proposed standardizing facilities across the base. The standardized structure design incorporated transportation costs, efficient packaging, easy constructability, and minimal solar efficiency gain. The second category proposed changes to the water treatment and recycling systems deployed at the base level. The analysis considered the deployment of a water treatment system accompanied by upgrades to the latrines and shower systems. By implementing these changes, the simulated contingency base reduced the peak power demand and water usage by 28% and 27%, respectively. This study highlighted that implementation of these select technologies at the base level could decrease fuel and water requirements, which reduces the costs of the supply chain.

The next four studies examine approaches to optimize the electrical demand in remote locations and are relevant because the techniques are similar to those found in this research. Combe et al. (2020) investigated the optimal configuration of hybrid power systems in a remote community in southern Australia using particle swarm optimization algorithms. These communities relied solely on an array of diesel generators to produce the required electricity for sustainment, creating high electricity costs. These high electrical costs drove the need to optimize infrastructure alternative combinations to reduce the overall electrical demand and minimize the environmental impact. The study considered hybrid systems as combinations of varying equipment such as diesel generators, battery storage devices, wind turbines, and photovoltaic systems. The results show a reduction in annual operations costs in electrical demand and CO_2 emissions for the community. Furthermore, the inclusion of battery power storage devices increased savings when combined with other alternative power generation equipment.

A similar study was conducted on remote communities in Habaswein, Kenya (Micangeli et al. 2017). This work focused on evaluating and optimizing micro-grid systems, including solar, wind, and power storage alternatives. A stochastic optimization model called Hybrid Optimization of Multiple Energy Resources (HOMER) software was utilized to simulate, optimize, and perform sensitivity analysis on the project site. This software specializes in evaluating design options for on and off-grid power systems for remote, stand-alone, and distributed power generation applications. The model considered capital costs, operational costs, fuel price dependency, and environmental emissions. The results highlighted that a hybrid configuration utilizing renewable technologies outperformed the existing base plant diesel generators in net present costs, electricity costs, and fuel demand over a 25-year plant lifetime. The reduction in electrical demand reduced the fuel demand and, therefore, can reduce greenhouse gas emissions by tens to hundreds of tons every year. M. Rumbayan applied HOMER software to a remote community on the Kokorotan Islands near Indonesia. The community consists of 881 people, and they have extremely limited access to electricity due to geographical inaccessibility and lack of electrical infrastructure (Rumbayan 2017). The limitations of the people on this island produced the need to establish the electrical requirements and analyze possible approaches to introducing sustainable technologies to the community. This analysis demonstrates that there are optimal system combinations possible by implementing elements of solar, wind, and battery systems at an affordable cost. Furthermore, there is potential for the hybrid system to generate excess energy to be utilized by the island inhabitants as backup power.

Pelet et al. (2005) developed a multiobjective optimization model that uses a genetic algorithm to balance tradeoffs between resources, demand, energy, emission, and cost in a remote Tunisian Saharan region. This research intended to find optimal solutions by either introducing new infrastructure or retrofitting the existing systems to limit CO_2 and overall costs. The results displayed that a 33% reduction in costs and a 51% reduction in CO_2 emissions can be reached by implementing a retrofitted electrical grid.

Studies have been performed at the network level to optimize large scale temporary housing layouts in preparation for natural disasters. El-Anwar et al. (2009) first developed an optimization model that is capable of (1) minimizes social and economic disruptions due to family displacement, (2) temporary housing vulnerabilities due to disasters, (3) adverse environmental impacts caused by construction and maintaining temporary housing sites, and (4) the cost of ownership of varying temporary housing solutions. The model utilizes mixed linear integer programming to calculate tradeoffs between combinations of alternative solutions. El Anwar et al. (2010) also created an optimization model that analyzed post-disaster alternative housing sustainability. This mixed linear integer programming model maximizes the sustainability of alternative housing combinations by considering four variables: (1) environmental, (2) social welfare, (3) economic, and (4) public safety variables performance. This tool helps decision makers select post-disaster housing alternatives by highlighting combinations of alternatives with maximized sustainability indexes.

Optimization Techniques at the Contingency Base & Remote Community Level

Optimization at the contingency base level, as opposed to the infrastructure level, is another approach to finding optimal solutions for specified criteria. One study in this research area focused on developing a cost-performance model capable of optimizing three infrastructure variables: solar array size, battery backup systems, and shelter insulation type for a remote community (Pearson et al. 2020a). The study aimed to reduce the total resource usage and cost of remote site sustainment by selecting optimal combinations of the aforementioned three variables. The model took into account the base size by performing analysis at the single shelter level, allowing for scalability. Climate interactions were also accounted for by integrating weather data into the analysis that produced the system energy requirements. This models' capabilities were demonstrated using two case studies with varying climate zones in southwest Asia and the Caribbean. The optimal configurations selected for these two sites had varying solar array sizes and lithium-ion battery configurations based on the differing site factors. These solutions reduced fuel usage by at least 92% and can save up to $562,000 over a one-year operating period compared to diesel generator configurations. This area of study was further researched by adapting the aforementioned model to a military scenario (Pearson et al. 2020b). This model is designed to select a hybrid energy system for an expeditionary environment while minimizing the transportation and lifecycle costs. A case study set on a military base in the Philippines was developed to illustrate the model's capabilities. The model selected a hybrid energy system consisting of a 676-kW photovoltaic array, 1,846-kWh battery systems, and a 200-kW generator. This near-optimal solution reduced the operational costs from $9.81 million to $4.99 million and had a calculated fuel reduction of 237,441 liters per year.

A similar approach to contingency base level optimization focused on the selection of stand-alone photovoltaic-battery systems sized and selected to replace legacy generator power systems (Thomsen et al. 2019). This research developed a cost-performance model capable of balancing tradeoffs between minimizing initial system cost and maximizing power reliability. A case study was performed to illustrate the model's ability to select varying solar array and storage systems in a contingency environment. The results demonstrated that the model successfully sizes a photovoltaic array and storage system while reducing the overall costs of operation and maintaining power generation reliability. The reduction in fuel consumption at the contingency base level translates to a savings of 1.9 million liters of fuel and a reduction of 100 fuel tanker delivers per year.

Optimization techniques have also been applied to other areas of contingency bases such as security and layout with respect to explosive attacks. The first two studies focused on identifying optimal tradeoffs between security and costs on contingency bases (Schuldt and El-Rayes 2018a; b). This study developed a multi-objective optimization model proficient in generating optimal tradeoffs between minimizing destruction levels from explosive attacks on critical buildings and infrastructure systems and minimizing the associated construction costs. The model included varying techniques to mitigate destruction from explosive attacks, such as varying standoff distance standards, blast mitigation wall construction, and facility hardening. Two application examples using hypothetical contingency bases were used to simulate the model’s capabilities. From these simulations, 117 near-optimal solutions for multiple explosive threats were generated at varying levels of acceptable destruction and varying explosion types. This model's contributions allow planners to efficiently evaluate many design solutions to balance acceptable levels of destruction and site construction costs while reducing the risk to site personnel and facilities from explosive attacks.

The last study in this section focused on minimizing impacts to personnel from explosive attacks and minimizing site construction costs (Schuldt et al. 2020). A facility layout optimization model was developed to quantify blast consequences from explosive attacks while generating optimal site layouts and protective measures based on the location and size of the attack. The model accounted for four consequences from explosive attacks (personnel loss, psychological impacts, economic loss, and operational impact), viable site layout configurations, and blast wall construction methods. A hypothetical case study was simulated to demonstrate the model's capability to generating optimal solutions between the competing objectives of minimizing impacts to personnel and construction costs. This model assists military planners in selecting optimal configurations and protection measures for varying base sizes and characteristics.

Contingency Base Classifications and Planning Factors

Contingency bases are generally classified by their population size and current mission, dictating different criteria such as footprint, authorized facilities, facility count, and infrastructure authorized. Table 1 visualizes how the classification of contingency base based on duration, type, size, and population vary across services and commands. The classification characteristics were extracted from the following four main sources regarding contingency bases: (1) U.S. Army Corp. of Engineers: Base Camp Development in the Theater of Operations (2009), (2) US Army Field Manual 3-34: Engineer Operations (2014), (3) US Army Europe Command: Standards for Base Camps-Red Book (2020), and (4) US Central Command: Construction and Base Camp Development-Sand Book (2004).

Table 1: Contingency base characterizations, adapted from Noblis (2010).

Duration				
USACE	Organic < 90 days	Initial < 6 months	Temporary < 24 months	Semi-Permanent
Army FM 3-34		Initial < 6 months	Temporary 6-24 months	Semi-Permanent 2-10 years
USAREUR "Red Book"		Initial < 6 months	Temporary 6-24 months	Semi-Permanent 2-10 years
USCENTCOM "Sand Book"	Expeditionary	Initial	Temporary	Permanent
Base Charctersistics				
Type	Forward Operating Base		Main Operations Base	Enduring/Permanent Base
Size & Population	Platoon-Company 25-350 Personnel		Battalion-Brigade 350-5,000 Personnel	Division 5,000-10,000 Personnel

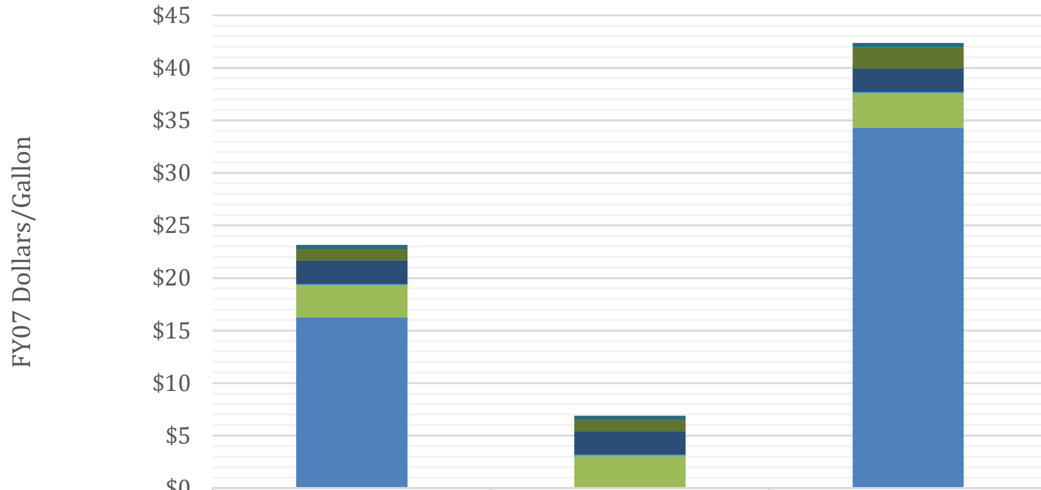
The aforementioned base characteristics are valuable to this research because they provide a basis to select the appropriate characteristics for the applied modeling techniques, further illustrated in this thesis.

Planning factors are another important aspect of contingency base planning within the literature. Planning factors are derived from infrastructure production assets that meet the base requirements, such as power and water production and disposal of generated wastes. In this research, infrastructure planning factors will be annotated by the number of categorical units per person per day to show the requirement or waste production for one person on the base. By quantifying the planning factor requirements in units required per person per day and then multiplying the value by the base population, the total base requirement can be represented numerically. Filer's research focused on four main types of planning factors: (1) power requirement, (2) potable water requirements, (3) solid waste production, and (4) wastewater production (Filer and Schuldt 2019). These planning factors represent the main requirements to operate and sustain a contingency base.

Power production infrastructure assets provide electrical input to the myriad of infrastructure equipment that a contingency base could be allocated based on its size and mission, such as HVAC, lighting, and communication equipment along with water production waste management equipment. For example, a small 50-person base will not require an extensive generator grid system to power all of its systems; conversely, an enduring base with over 10,000 personnel would not be able to produce enough electricity efficiently with many small generators. The overall base power production requirement can be calculated based on the demand of all the electrical power equipment and then divided by the base population to produce the power production planning factor. Some calculated planning factors for power production vary between 2 KW/person on the high end and 0.32 KW/person on the low end (Pickard 2003; USAHQ 2014).

Potable water, wastewater, and solid waste production planning factors can be calculated from the base population size and demand requirements. Potable water production requirements range from 22 to 60 gallons per person per day (USAHQ 2014; USAREUR 2004). For wastewater, including greywater and blackwater, a typical contingency base can range from 29 to 50 gallons of wastewater produced per person per day (Pickard 2003; USAHQ 2014; USAREUR 2020). On average, greywater makes up roughly 85% of all the wastewater produced on a contingency base, with the other 15% being non-reusable black water (Noblis 2010). Solid waste produced at contingency bases is comprised mainly of packaging material, plastic, and wood. Planning factors for solid waste have been reported to range widely between 4 to 28 pounds per person per day (Conkle 1999; Ruppert et al. 2004). The variance between these planning factors is due to contingency bases having different locations, populations, missions, assets allocation, and asset quantity availability (Noblis 2010).

More often than not, contingency bases are not connected to the local infrastructure grid, making power production via generators to run cooling, heating, and lighting assets, the only viable option. This approach is a costly and constant challenge to maintain (GAO 2009). Local power grids in the area of operations can be unstable and or produce alternate power supplies, making their use less than ideal or not an option due to standard contingency asset power input requirements. Thus, the military relies on generators and generator grid systems to supply uninterrupted power to the contingency base population. Generators are the single largest fuel consumer at contingency and main operating bases (GAO 2009). For example, Army generators alone consume about 26 million gallons of fuel annually during peacetime and roughly 357 million gallons during wartime (GAO 2009). The fully burdened cost of fuel has been a viable way to measure the cost of fuel transported to contingency bases. The components of the fully burdened cost of fuel vary by source. Generally, they include distribution costs such as force protection, transportation type (air or ground), and distance to the delivery site, plus the varying cost of the fuel itself. The Noblis report cited variable costs per gallon for the fully burdened cost of fuel (Figure 2), ranging from $25.16 as a base case without transportation distance (Scenario 1), $9.04 delivered by air (Scenario 2), and $44.40 as the base case with transportation to a contingency location 950 miles away (Scenario 3).



	1	2	3
Materiel	$0.40	$0.40	$0.40
Transport	$1.06	$1.06	$2.02
SBCT personnel	$2.28	$2.28	$2.28
Sust. brigade	$0.13	$0.13	$0.13
FP (ground)	$3.03	$3.03	$3.23
FP (air)	$16.25	$0.00	$34.31

Figure 2: Fully burdened cost of fuel, adapted from Noblis (2010).

The components of the fully burdened cost of fuel from Figure 2 are defined and described as: (1) materiel which accounts for the maintenance material required for the transportation vehicles, (2) transport component consists of the efficiency of the vehicles being used in the convoys and distance to the end location, (3) SBCT (Stryker Brigade Combat Team) personnel is the cost of protection personnel assigned to the convoy, (4) sustainment brigade accounts for the personnel at the main operating base that maintain the convoy vehicles, (5) FP (Force Protection) ground resembles the cost of force protection vehicles and weapons attached to the convoy, (6) FP (Force Protection) air shows the cost to have combat support from air assets assigned to escort the convoy to the final destination.

Contingency base fuel usage is directly related to the power production planning factors due to the heavy reliance on generators, as previously mentioned. Fuel planning factors can be calculated based on the base population and the power requirements. Reported ranges for this planning factor vary from 1 gallon per person per day at a minimal 25-person tactical outpost to 5.6 gallons per person per day at a 15,000-man expeditionary contingency base with an aviation component (USAHQ 2014). The overall fuel planning factor for the latter base with the aviation component had an overall requirement of 33 gallons per person per day, but only 17% of the fuel planning factor was used for base sustainment.

Literature Gap

The literature above encompasses the current state of knowledge around contingency base sustainability and optimization techniques. Many studies analyze the employment of varying infrastructure technologies at remote or isolated locations. Still, none that this researcher has found specifically optimizes costs and infrastructure alternative performance metrics in a military scenario within a network. This research intends to fill that gap by quantifying and optimizing the selection based on the cost and performance variables. Optimal selection of infrastructure alternatives at the contingency base level can reduce the sustainment costs and demand for resupply, which affects the contingency base level and the resupply network.

III. Methodology

Introduction

This chapter illustrates the methods applied to develop the optimization model for this research. The first section summarizes the base level functions and infrastructure categories considered for the development of the model. The next section highlights the relevant resources and the baseline resource usage that the legacy equipment requires to sustain the contingency base. Next, the infrastructure alternatives within each infrastructure category are presented, followed by the development of the decision variables, cost metric, performance metric, and the objective function.

Base Level Functions and Infrastructure Categories

The first step in gathering the data for this study was to analyze the various functions that a contingency base must supply to the personnel for continued sustainment. The initial SLB-STO-D report titled Operationally Relevant Technical Baseline (2016) gathered and organized various function level-requirements at the contingency base level for three varying base populations (50, 300, 1,000) and three climate zones (desert, temperate, tropical). These requirements include providing access to: (1) electrical power, (2) shelter, (3) subsistence, (4) potable water, (5) personal hygiene services, (6) latrines services, (7) laundry services, (8) solid waste management, and (9) liquid waste management. The nine function-level requirements can be translated into 12 infrastructure categories at the infrastructure equipment level: (1) shelter, (2) power generation, (3) subsistence-food preparation, (4) subsistence-refrigeration, (5) water heating, (6) metering and monitoring, (7) laundry services, (8) personal hygiene, (9) potable water management, (10) latrine services, (11) wastewater management, and (12) solid waste management. The infrastructure categories are derived from the function-level requirements by utilizing equipment such as generators, temper tents, tri-con kitchen units, latrines, and shower units.

Infrastructure Resources

To sustain the equipment at the contingency base, raw resources (fuel and potable water) are required to be delivered, while generated waste (solid and liquid waste) is required to be disposed of. The aforementioned SLB-STO-D report performed analysis on legacy infrastructure equipment to develop baseline values of daily resource requirements. U.S. Army Natick used software called Detailed Component Analysis Model (DCAM) to simulate the daily fuel, potable water requirements, and waste production of a contingency base across varying climates. Table 2 visualizes the total daily demands for the 300-personnel contingency base in desert, temperate, and tropical climate zones utilizing legacy equipment. This research focuses on minimizing the fuel and potable water variables because they are the two primary resources resupplied at high volumes to sustain a contingency base.

Table 2: Camp level summary, 300 PAX, adapted from US Army NATICK (2016).

Resource Type	Desert	Temperate	Tropical
Fuel Demand (liters/day)	3,944	4,149	3,872
Potable Water Demand (liters/day)	33,020	33,020	33,020
Waste Water Generation (liters/day)	32,286	32,286	32,286
Solid Waste Generation (kilogram/day)	1,302	1,302	1,302

Infrastructure Alternatives

Many infrastructure alternatives are viable options to replace legacy equipment on a contingency base due to improved efficiency and performance characteristics. Tactics-Techniques-Procedures (TTP) are non-equipment changes that a commander can implement at the contingency base level with minimal associated costs while reducing the overall resource usage. For example, by implementing a 5-minute shower policy instead of a 10-minute shower, the total potable water usage is reduced from 20,802 to 15,484 liters per day.

This research evaluates 47 infrastructure options, including legacy equipment and infrastructure alternatives. These infrastructure options are considered due to their performance ability in a military capacity and available performance data. The number of alternatives varies between infrastructure categories, but there is a minimum of one infrastructure alternative available for consideration other than the legacy equipment in each category. Table 3 visualizes all of the considered alternatives within their respective infrastructure category, the type of alternative, and the required equipment count needed to sustain the 300-person contingency base.

The legacy equipment is shown as the first row in each infrastructure category. Some alternatives include a combination of equipment and or a combination of equipment and TTPs. For example, alternative 5 includes a V1.5 AS TEMPER Tent liner along with a Photovoltaic Shade or Pshade system. Combining these two alternatives reduces resource consumption when applied to the shelter systems more than if one alternative was deployed alone.

DCAM was used to simulate the impact on fuel and potable water requirements when a single infrastructure alternative was deployed in place of the legacy equipment. The infrastructure alternative impact values were calculated as a percentage decrease or increase from the baseline totals of fuel and potable water (US Army NATICK 2017). To obtain the daily fuel and water usage of a single alternative, distribution percentages were applied to legacy equipment in each infrastructure category, resulting in liters required per day of the legacy equipment. The notation in the following equations is represented by infrastructure alternatives, i, within infrastructure categories, j, at various contingency bases, k. Equation (**1** represents the mathematical approach to produce the resource usage of fuel and potable water per day of an infrastructure alternative by applying the infrastructure category resource percentage and the legacy equipment resource usage (US Army NATICK 2017).

Table 3: Infrastructure alternative database and characteristics.

Infrastructure Group	Alt. Count	Infrastructure Alternative	Alt. Type	Equip. Count
A (Shelter)	1	AS TEMPER Tent	Equipment	23
	2	Liner-V1.5	Equipment	23
	3	Shade-ULCANS	Equipment	23
	4	Shade-PShade	Equipment	23
	5	V1.5 Liner & PShade	Equipment	23
	6	V1.5 Liner & ULCANS	Equipment	23
	7	18 PAX per AS TEMPER Tent	TTP	18
	8	Eliminate Convenience Loads	TTP	23
B (Power Generation)	9	60kW Tactical Quiet Generator (TQG)	Equipment	24
	10	TM 3-34.46 Layout - 60kW TQGs	TTP	17
	11	Hybrid Power Trailer (HPT)	Equipment	24
	12	T-100 (Towable Generator System)	Equipment	24
	13	Realistic Grid - 60kW TQGs	Equipment	14
	14	One Large Grid - 60kW TQGs	Equipment	10
C (Subsistence)	15	Expiditionary TRICON Kitchen System (ETK)	Equipment	2
	16	Fuel-Fired ETK	Equipment	2
D (Refrigeration)	17	Multi Temp. Refrigeration Container System	Equipment	4
	18	High Efficiency MTRCS	Equipment	4
	19	High Efficiency MTRCS & Solar Array Shade	Equipment	4
E (Water Heating)	20	WH-400 & Modern Burner Unit System (MBU)	Equipment	6
	21	Solar Water Heater System	Equipment	12
F (Metering)	22	No metering/Monitoring	N/A	6
	23	Nonintrusive Load Monitoring (NILM) & Deployable	Equipment	6
G (Laundry Services)	24	20-lb commercial washers	Equipment	8
	25	1/2 Laundry Usage per week	TTP	8
H (Personal Hygiene Services)	26	10 Min Showers	TTP	0
	27	5 Min Showers	TTP	0
	28	Low Flow Shower Heads	Equipment	25
	29	5 Min Showers & Low Flow Shower Heads	Equipment	25
I (Water Production)	30	Bulk Water Resupply	Resupply	0
	31	Tactical Water Purificaiton System (TWPS)	Equipment	1
J (Latrine Services)	32	Expiditionary Latrine System (ELS)	Equipment	6
	33	ELS & Solid Waste Flush Only	TTP	6
	34	ELS & Pipe Urinals	Equipment	10
	35	ELS & Waterless Urinals	Equipment	6
	36	Burn-Out Latrines	Equipment	10
	37	Chemical Latrines	Equipment	6
	38	Low Cost TRICON Latrine System (LCTL)	Equipment	3
K (Waste Water Mngt.)	39	Bulk Waste Water Disposal	Contract	0
	40	Forward Osmosis/Reverse Osmosis Graywater	Equipment	3
	41	Black Water Recycler	Equipment	3
	42	Deployable Baffled Bioreactor (DBBR)	Equipment	3
	43	FORO & DBBR	Equipment	4
L (Solid Waste Mngt.)	44	Bulk Solid Waste Disposal	Contract	0
	45	Open Air Burn Pit	Equipment	1
	46	Incinerator	Equipment	6
	47	Solid Waste Destruction System (SWDS)	Equipment	3

$$Q_i = LR_i\left(1 - IA_i^{percent\ \Delta}\right) \tag{1}$$

Where Q_i = infrastructure alternative resource usage of fuel or water (liters/day);

LR_i = legacy equipment resource usage (liters/day); and

$IA_i^{percent\ \Delta}$= infrastructure alternative impact on resource usage (%).

Table 4 shows the varying distribution of fuel and water usage broken down by infrastructure category. Select infrastructure categories do not have allocation percentages because the legacy infrastructure combination does not impact fuel or potable water usage, or the category was not utilized in the baseline analysis. For example, the legacy system for water production is resupplied by bulk water delivery from military convoy operations. Another example is the metering and monitoring category. There is no metering and monitoring system applied to the baseline simulations. When there is no fuel allocation, an assumption is made based on the infrastructure alternative impact value produced from the SLB-STO-D report.

Table 4: Infrastructure category resource distributions.

Fuel Distribution			Water Distribution		
Category	Percent of Total	Liters/Day	Category	Percent of Total	Liters/Day
Shelter	6%	237	Shelter	0%	-
Power	73%	2,879	Power	0%	-
Subsistence	5%	197	Subsistence	4%	1,321
Refrigeration	1%	39	Refrigeration	0%	-
Water Heating	1%	39	Water Heating	0%	-
Metering	0%	-	Metering	0%	-
Laundry	2%	79	Laundry	9%	2,972
Hygiene	5%	197	Hygiene	63%	20,803
Water Production	0%	-	Water Production	0%	-
Latrines	7%	276	Latrines	24%	7,925
Waste Water	0%	-	Waste Water	0%	-
Solid Waste	0%	-	Solid Waste	0%	-
Total	100%	3,944	Total	100%	33,020

All of the infrastructure alternatives considered affect fuel usage, but not all alternatives affect potable water usage. For example, the shelter category only affected the fuel usage, while the subsistence category affected both fuel and water usage.

Decision Variables

The decision variables used in this optimization model are the infrastructure alternatives within infrastructure categories that can be selected to impact the overall costs and resource usage at the contingency base level. Thirty-five infrastructure alternatives and twelve legacy equipment options are considered in this research (42 total infrastructure assets). The model considers various infrastructure alternatives, i, that are encompassed by the infrastructure categories, j, at various contingency bases, k. The infrastructure categories were selected because of the high impact they have on fuel and potable water usage at the contingency base level. Each infrastructure category must fill the contingency base requirements with the selection of one infrastructure system.

Cost Metric

The cost metric was developed to calculate the total cost of an infrastructure combination, including the cost to procure, deliver, maintain, and resupply the infrastructure alternative over time. This total cost value is the sum of the costs associated with each selected alternative within the 12 infrastructure categories and is represented by Equation (2.

$$AC_k = \sum_{j=1}^{J} (CI_i + CM_i + CF_i + CW_i) \quad (2)$$

Where AC_k = total cost of alternative combo over an operational duration ($);

CI_i = total initial cost of infrastructure alternative ($)

CM_i = alternative maintenance cost over operational duration ($)

CF_i = resupplied fuel cost of alternative over operational duration ($);

CW_i = resupplied water cost of alternative over operational duration ($);

The initial cost of an alternative includes initial procurement and transportation costs, as shown in Equation (3.

$$CI_i = (CP_i \, Q_i) + CT_i \quad (3)$$

Where CP_i = procurement cost of infrastructure alternative ($);

Q_i = quantity of infrastructure alternatives required (#);

CT_i = transportation cost of alternative ($);

The transportation cost of an alternative is calculated using Equation (4 by accounting for the units' weight, travel distance from the main operating base to the specified contingency base, and associated transportation and logistics costs. The transportation cost was applied based on the total weight per 100 kilograms of the alternative to be transported and is visualized by Table 5 (Lojistic 2020).

Table 5: Transportation cost by weight category.

Weight Category (Kg/100)	Rate
0 - 226.34	$45.00
226.79 - 453.13	$35.00
453.59 - 906.73	$30.00
907.18 - 2,267.50	$28.00
2267.96 - 4,535.47	$20.00
4,535.92 - 9,071.84	$19.00

The logistics costs were adapted from the fully burdened cost of fuel as defined by Noblis (2010). All components of fully burdened cost were adjusted to 2020 values to account for inflation. The equation also takes into account the efficiency of the transportation vehicles utilized. The value of this efficiency factor was selected as 1.7 kilometers per liter (4 miles per gallon) when a M1120 HEMTT LHS transportation truck is used (USAHQ 2009).

$$CT_i = \left(\frac{W_i\, Q_i}{wf} F\right) + \left(\frac{CL\, d}{\gamma}\right) \tag{4}$$

Where W_i = weight of a single infrastructure alternative (kg);

wf = weight factor, converts weight into quantity per 45.35 kgs;

F = weight cost factor ($);

CL = fully burdened cost of transportation logistics ($/liter);

d = distance to contingency base (km); and

γ = efficiency factor of ground transportation vehicle (km/liter).

The fully burdened cost of fuel and water is calculated by Equations (5 and (6, respectively. The equations integrate all of the components of the fully burdened cost of fuel as defined by Noblis (2010) to calculate the cost to transport fuel and potable water to the contingency bases for resupply. Cost components used in these equations were adjusted to 2020 values to account for inflation and the use of commodity prices for fuel and potable water. The equation accounts for the quantity of fuel or water that an infrastructure alternative requires over an operations time period and the cost to transport the resources over a specified distance.

$$CF_i = (FQ_i\ (t)\ FC) + \left(\frac{FV_i\ (CL)\ d}{\gamma}\right) \tag{5}$$

Where FQ_i = alternative fuel usage per day (liter/day);

t = duration of operations (days);

FC = fuel commodity price ($/liter);

FV_i = number transportation trucks required to resupply fuel;

$$CW_i = (WQ_i\ (t)\ WC) + \left(\frac{WV_i\ (CL)\ d}{\gamma}\right) \tag{6}$$

Where WQ_i = alternative water usage per day (liters/day);

WC = water commodity price ($/liter);

WV_i = transportation trucks required to resupply water;

Resource Metric

The resource metric was developed to represent the fuel and potable water usage of an alternative over a specified time period in liters per day. The daily resource usage values for fuel and potable water were calculated using Equation (**1**, which converted the impact values of an alternative from percentage to liters per day of resource usage. The total resource usage over time of an infrastructure alternative is calculated by multiplying the resource usage measured in liters per day by the specified time duration.

Finally, the fuel and potable water performance values of the selected infrastructure alternatives at a contingency base are summed to produce one single performance metric representing contingency base resource usage in liters over time, as shown by Equation (7.

$$AR_k = \sum_{j=1}^{J} \left(WQ_i(t) + \ FQ_i(t) \right) \tag{7}$$

Where AR_k = alternative resource usage over the duration of operations (liters);

Objective Function

After calculating the cost and performance metrics, the values were normalized using the min-max technique. Equations (8 and (9 show how the normalized values at the contingency base level were calculated. This nominalization technique converts the cost and performance variables to unitless values between 0 and 1. A value of 0 represents the lowest cost or performance of an alternative combination, and a value of 1 represents the highest cost or performance of an alternative combination. This action allows for variables of different units and orders of magnitude to be compared.

$$AC_k^{norm} = \frac{AC_k - \min(AC_k)}{\max(AC_k) - \min(AC_k)} \tag{8}$$

$$AR_k^{norm} = \frac{AR_k - \min(AR_k)}{\max(AR_k) - \min(AR_k)} \tag{9}$$

Where AC_k^{norm} = nominalized alternative combination cost over operational duration;

AR_k^{norm} = nominalized alternative combination performance over an operational duration.

Furthermore, weights, $\mathrm{wt}_{\mathrm{AC}}$, and $\mathrm{wt}_{\mathrm{AR}}$, are applied to represent the military planners' priorities to minimize cost and performance. These two weights are applied to the normalized cost and performance variables to influence the selection of infrastructure alternatives.

Finally, the objective function is shown in Equation (10.

$$minimize\ AS_k = wt_{AC}\ AC_k^{norm} + wt_{AR}\ AR_k^{norm} \quad (10)$$

Where AS_k = infrastructure alternative combination score over an operational

duration

for a specified contingency base;

wt_{AC} = importance weight of cost; and

wt_{AR} = importance weight of resource usage.

This equation is utilized to calculate an infrastructure alternative combination score, AS, while selecting infrastructure alternative combinations for multiple contingency bases within a hub-and-spoke network. This minimization function works to select a single infrastructure alternative within each infrastructure category at every contingency base that minimizes the total costs and resource usage required to sustain a single contingency base based on the military planners' priorities.

IV. Analysis and Results

Introduction

This section applies the aforementioned optimization model to a hypothetical case study to demonstrate the model's capabilities in balancing tradeoffs between cost and performance. The first section summarizes and describes the hypothetical contingency base characteristics and the military logistics network associated with the hypothetical contingency base. The next section analyzes the results produced by the optimization model. Weighted scenarios with varying infrastructure combinations are compared to highlight the variation between outputs. Next, the cost and resource usage of the weighted scenarios are compared to illustrate how these variables change over time between the two contingency bases. The final section summarizes the results of the model outputs and highlights the key takeaways.

Case Study

A theoretical scenario with a military hub-and-spoke network consisting of two contingency bases is developed to apply the model and display its capabilities. Contingency base Alpha and Bravo are set in the north-east mountainous region of Afghanistan located at varying distances south-east from a large, established main operating base, Bagram Airfield. Figure 3 shows the main operating base, contingency bases, travel distance from MOB to the contingency bases, and the surrounding area of operation. Bagram Airfield, a joint main operating base, has been in coalition control since 2001 and has had a sizeable estimated population of coalition troops ranging from

3,000 to 7,000 (Gibbons-Neff 2020). The duration of operations and personnel count of Bagram Airfield put the base in the enduring category, making it a viable option to serve as a hub in the hypothetical hub-and-spoke network model.

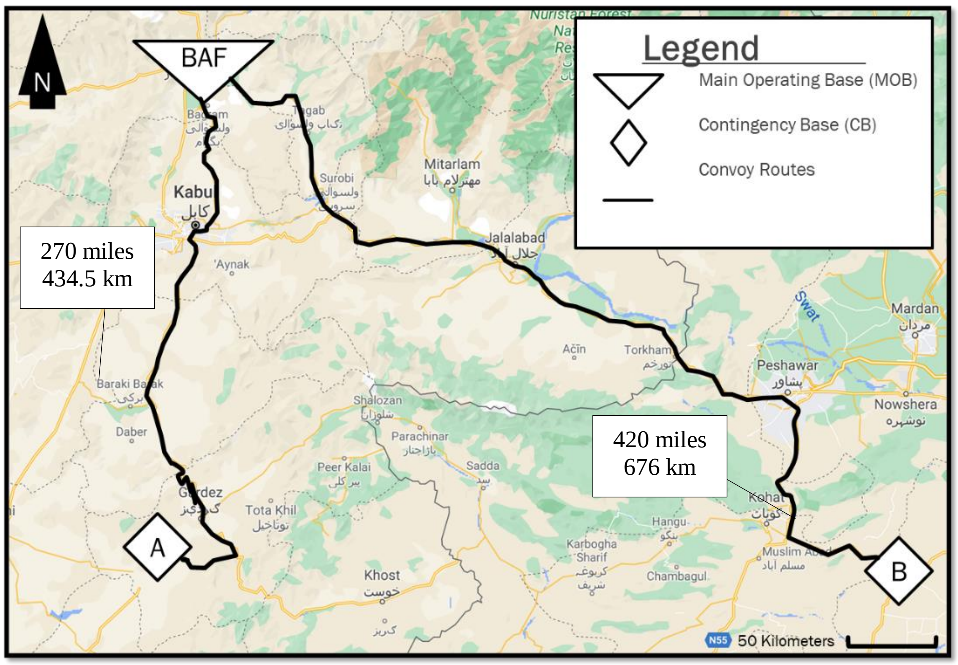


Figure 3: Case study area of operations.

The theoretical contingency bases Alpha and Bravo were selected to have 300 personnel in a steady-state environment with minimal variation in personnel residing on the base from day to day with a projected operational period of six years. The 300-person contingency base population was selected because there is substantial performance data for an extensive array of infrastructure alternatives provided by the SLB-STO-D report (US Army NATICK 2017). A contingency base with a population of less than 300 personnel does not have as many infrastructure alternatives for consideration.

Ground vehicle resupply is the targeted transportation method in this study because convoy logistics operations make up a large and complex portion of the costs associated with contingency base sustainment (Putnam et al. 2016). Contingency bases Alpha and Bravo have varying ground transportation distances of 434.5 kilometers and 676 kilometers, respectively. The U.S. military frequently utilizes the M1120 HEMTT LHS transportation vehicle to transport resources and equipment from one location to another (US Army NATICK 2017). This vehicle has a material capacity of 19,958 kilograms. The M1120 HEMTT LHS also comes in two variants allowing for bulk fuel or bulk potable water transportation. This bulk liquid transportation variant has an 18,927 liter capacity for fuel and a 15,141 liter capacity for potable water (US Army NATICK 2017). The initial delivery of infrastructure equipment selected for a contingency base, along with the resupply of fuel and potable water, are delivered via ground transportation from the Bagram Airfield to contingency base Alpha and Bravo. The vehicle performance efficiency for the M1120 HEMTT LHS is 1.7 kilometers per liter (USAHQ 2009). This vehicle efficiency factor is used in the delivery costs of equipment and resupply materials.

A baseline scenario was adapted from the SLB-STO-D report to establish the contingency bases' overall baseline performance values. This simulation utilized the legacy equipment, climate zone, and personnel count to produce resource usage of fuel and potable water and waste generation per day on the camps. Table 6 shows the calculated baseline quantities for fuel, potable water, solid waste generation, and liquid waste generation.

Table 6: Resource consumption and waste generation.

Resource Type	CB Bravo
Fuel Demand (liters/day)	3,944
Potable Water Demand (liters/day)	33,020
Waste Water Generation (liters/day)	32,286
Solid Waste Generation (kilogram/day)	1,302

These baseline values resemble the daily requirement that infrastructure equipment must deliver or dispose of to sustain the contingency base. Some of the baseline values are met by contracts established with the local community, such as wastewater and solid waste disposal.

The infrastructure alternatives and performance data in this research were adapted from the SLB-STO-D analysis report produced by U.S. Army Natick in 2017. illustrates the values of cost, fuel usage, and potable water usage of the various infrastructure alternatives within each infrastructure category over a 24-hour period of operation before normalization at contingency base Alpha. Contingency base Bravo's values can be seen in the Appendix. The cost column includes the cost of procurement, initial delivery, maintenance, and resupply over a 24-hour period of operation. Some of the alternatives include equipment changes, TTP changes, combinations of equipment changes, and combinations of equipment and TTP changes. When deployed in conjunction, these combinations have a more significant effect on fuel and potable water usage than if they were deployed as a single alternative.

The constraints of the model are as follows: (1) the selection outputs were constrained to binary, (2) the outputs must be non-negative values, and (3) a single infrastructure alternative must be selected from each infrastructure category. The optimization model utilizes weighted, normalized cost and performance values to select a single alternative within each of the 12-infrastructure categories. This method produces a binary output signifying that the infrastructure alternative was selected for that particular infrastructure category in a specific weighted scenario. After the optimization was run, the total cost and resource usage values can be summed to represent the infrastructure alternative combination values. These infrastructure alternative combinations represent optimized contingency base portfolios for the specified military planner priorities.

The model optimizations were ran using Simplex Linear Programming (LP) solving method within Microsoft Excel 2016, and the figures were also developed in Microsoft Excel 2016 (Microsoft-Office 2016).

Table 7: Case study infrastructure alternatives database at initial setup.

Infrastructure Group	Alt. Count	Infrastructure Alternative	Alt. Type	Equip. Count	Total Cost	Fuel Usage (liters)	Potable Water Usage (liters)
A (Shelter)	1	AS TEMPER Tent	Equipment	23	$ 426,444	237	-
	2	Liner-V1.5	Equipment	23	$ 464,039	215	-
	3	Shade-ULCANS	Equipment	23	$ 429,430	216	-
	4	Shade-PShade	Equipment	23	$ 571,578	223	-
	5	V1.5 Liner & PShade	Equipment	23	$1,034,717	214	-
	6	V1.5 Liner & ULCANS	Equipment	23	$ 892,568	207	-
	7	18 PAX per AS TEMPER Tent	TTP	18	$ 333,932	224	-
	8	Eliminate Convenience Loads	TTP	23	$ 426,447	232	-
B (Power Generation)	9	60kW Tactical Quiet Generator (TQG)	Equipment	24	$ 633,119	2,879	-
	10	TM 3-34.46 Layout - 60kW TQGs	TTP	17	$ 448,872	2,313	-
	11	Hybrid Power Trailer (HPT)	Equipment	24	$2,301,265	2,001	-
	12	T-100 (Towable Generator System)	Equipment	24	$1,944,083	2,512	-
	13	Realistic Grid - 60kW TQGs	Equipment	14	$ 794,618	1,697	-
	14	One Large Grid - 60kW TQGs	Equipment	10	$ 868,018	1,520	-
C (Subsistence)	15	Expiditionary TRICON Kitchen System (ETK)	Equipment	2	$ 157,858	197	1,321
	16	Fuel-Fired ETK	Equipment	2	$ 178,489	191	1,332
D (Refrigeration)	17	Multi Temp. Refrigeration Container System	Equipment	4	$ 179,569	39	-
	18	High Efficiency MTRCS	Equipment	4	$ 187,556	39	-
	19	High Efficiency MTRCS & Solar Array Shade	Equipment	4	$ 236,682	39	-
E (Water Heating)	20	WH-400 & Modern Burner Unit System (MBU)	Equipment	6	$ 153,482	39	-
	21	Solar Water Heater System	Equipment	12	$ 381,800	39	-
F (Metering)	22	No metering/Monitoring	N/A	6	$ 55	76	-
	23	Nonintrusive Load Monitoring (NILM) & Deployable	Equipment	6	$ 13,318	49	-
G (Laundry Services)	24	20-lb commercial washers	Equipment	8	$ 8,656	79	2,972
	25	1/2 Laundry Usage per week	TTP	8	$ 8,593	78	2,844
H (Personal Hygiene Services)	26	10 Min Showers	TTP	0	$ 10,361	197	20,803
	27	5 Min Showers	TTP	0	$ 7,747	195	15,485
	28	Low Flow Shower Heads	Equipment	25	$ 10,440	196	17,380
	29	5 Min Showers & Low Flow Shower Heads	Equipment	25	$ 7,826	194	12,062
I (Water Production)	30	Bulk Water Resupply	Resupply	0	$ 25,907	-	-
	31	Tactical Water Purificaiton System (TWPS)	Equipment	1	$ 253,088	204	-
J (Latrine Services)	32	Expiditionary Latrine System (ELS)	Equipment	6	$ 322,175	276	7,925
	33	ELS & Solid Waste Flush Only	TTP	6	$ 321,540	276	6,633
	34	ELS & Pipe Urninals	Equipment	6	$ 318,533	273	5,895
	35	ELS & Waterless Urinals	Equipment	6	$ 322,497	276	7,358
	36	Burn-Out Latrines	Equipment	10	$ 42,694	251	5,916
	37	Chemical Latrines	Equipment	24	$ 21,946	276	7,358
	38	Low Cost TRICON Latrine System (LCTL)	Equipment	3	$ 193,928	307	6,097
K (Waste Water Mngt.)	39	Bulk Waste Water Disposal	Contract	0	$ 364	-	-
	40	Forward Osmosis/Reverse Osmosis Graywater	Equipment	3	$ 760,450	136	-
	41	Black Water Recycler	Equipment	3	$ 552,508	273	-
	42	Deployable Baffled Bioreactor (DBBR)	Equipment	3	$1,063,339	227	-
	43	FORO & DBBR	Equipment	4	$ 412,979	91	-
L (Solid Waste Mngt.)	44	Bulk Solid Waste Disposal	Contract	0	$ 344	-	-
	45	Open Air Burn Pit	Equipment	1	$ 5,058	76	-
	46	Incinerator	Equipment	6	$ 937,191	598	-
	47	Solid Waste Destruction System (SWDS)	Equipment	3	$ 780,726	64	-

Optimization Model Output Analysis: Contingency Base Alpha

The optimization model was run for both contingency base Alpha and Bravo simultaneously while varying the military planners' weighted criteria. The weighting scenarios were varied between cost and performance variables at 0.1 intervals, producing 11 infrastructure combinations for each contingency base (22 total infrastructure combinations).

Table 8 shows the weighted scenarios in columns and the selected infrastructure alternatives within each infrastructure category for contingency base Alpha. Seven of the 11 weighted scenarios produced unique alternative combinations and can be seen highlighted in light blue. The weighted scenarios of cost equal to 0.7 to the cost-weighted value of 0.4 were calculated to have the same infrastructure combinations. The following paragraphs analyze the selection of infrastructure alternatives for contingency base Alpha.

The shelter infrastructure category has seven infrastructure alternatives that change the legacy AS Temper tents' performance and cost. The most cost-effective option, a TTP that increase the personnel housed in each tent from 14 to 18, is selected from a cost-weighted value of 1.0 to 0.2. This alternative reduced the number of shelter systems required from 23 to 18 tents. This reduction in shelter systems also reduces the total cost by $92,500 and the fuel usage by 12.72 liters per day when compared to the baseline. When cost performance was weighted at 0.1 and the performance value at 0.9, the ULCANS alternative is selected. This currently fielded shade system is installed over the top of an existing tent, creating a barrier and thermal layer between the tent and the exterior elements. This technology reduces the solar radiation absorbed by the tents, reducing the shelter systems' overall fuel usage by 20.66 liters with an increased cost of $2,986. At a resource performance weight of 1.0, the military planners' only priority is minimizing the resource usage of fuel and potable water.

Table 8: Optimization results for contingency base Alpha.

Infrastructure Group	Alt. Count	Infrastructure Alternative	Baseline Scenario	Cost=1 Res.=0	Cost=.9 Res.=.1	Cost=.8 Res.=.2	Cost=.7 Res.=.3	Cost=.6 Res.=.4	Cost=.5 Res.=.5	Cost=.4 Res.=.6	Cost=.3 Res.=.7	Cost=.2 Res.=.8	Cost=.1 Res.=.9	Cost=0 Res.=.1
A (Shelter)	1	AS TEMPER Tent	X											
	2	Liner-V1.5												
	3	Shade-ULCANS											X	
	4	Shade-PShade												
	5	V1.5 Liner & PShade												
	6	V1.5 Liner & ULCANS												X
	7	18 PAX per AS TEMPER Tent		X	X	X	X	X	X	X	X	X		
	8	Eliminate Convenience Loads												
B (Power Generation)	9	60kW Tactical Quiet Generator (TQG)	X											
	10	TM 3-34.46 Layout - 60kW TQGs		X	X									
	11	Hybrid Power Trailer (HPT)												
	12	T-100 (Towable Generator System)												
	13	Realistic Grid - 60kW TQGs												
	14	One Large Grid - 60kW TQGs				X	X	X	X	X	X	X	X	X
C (Subsistence)	15	Expiditionary TRICON Kitchen System (ETK)	X	X	X	X	X	X	X	X				
	16	Fuel-Fired ETK									X	X	X	X
D (Refrigeration)	17	Multi Temp. Refrigeration Container System (MTRCS)	X	X	X	X	X	X	X	X	X	X	X	
	18	High Efficiency MTRCS												
	19	High Efficiency MTRCS & Solar Array Shade												X
E (Water Heating)	20	WH-400 & Modern Burner Unit System (MBU)	X	X	X	X	X	X	X	X	X	X	X	
	21	Solar Water Heater System												X
F (Metering)	22	No metering/Monitoring	X	X	X	X								
	23	Nonintrusive Load Monitoring (NILM) System					X	X	X	X	X	X	X	X
G (Laundry Services)	24	20-lb commercial washers	X											
	25	1/2 Laundry Usage per week		X	X	X	X	X	X	X	X	X	X	X
H (Personal Hygiene Services)	26	10 Min Showers	X											
	27	5 Min Showers		X										
	28	Low Flow Shower Heads												
	29	5 Min Showers & Low Flow Shower Heads			X	X	X	X	X	X	X	X	X	X
I (Water Production)	30	Bulk Water Resupply	X	X	X	X	X	X	X	X	X	X	X	X
	31	Tactical Water Purificaiton System (TWPS)												
J (Latrine Services)	32	Expiditionary Latrine System (ELS)	X											
	33	ELS & Solid Waste Flush Only												
	34	ELS & Pipe Urninals												
	35	ELS & Waterless Urinals												
	36	Burn-Out Latrines					X	X	X	X	X	X	X	X
	37	Chemical Latrines		X	X	X								
	38	Low Cost TRICON Latrine System (LCTL)												
K (Waste Water Mngt.)	39	Bulk Waste Water Disposal	X	X	X	X	X	X	X	X	X	X	X	X
	40	Forward Osmosis/Reverse Osmosis Recycling (FORO)												
	41	Black Water Recycler												
	42	Deployable Baffled Bioreactor (DBBR)												
	43	FORO & DBBR												
L (Solid Waste Mngt.)	44	Bulk Solid Waste Disposal	X	X	X	X	X	X	X	X	X	X	X	X
	45	Open Air Burn Pit												
	46	Incinerator												
	47	Solid Waste Destruction System (SWDS)												

In this scenario, the alternative combination of a V1.5 liner and the ULCANS shade is selected. This combination includes an improved interior liner and insulation systems to be installed in conjunction with the ULCANS Shade that was previously described. By selecting this equipment alternative combination, the shelter systems' daily fuel usage is reduced by 29.60 liters per day, with an increased total cost of $466,124 compared to the baseline.

The power generation infrastructure category consists of various generator systems and layouts that supply power to the camp. This infrastructure category has the largest influence on the fuel usage and cost variables in this model. At the weighted scenarios of cost equal to 1.0 and 0.9, the least expensive option is selected. This TTP alternative is to deploy the legacy 60 kW Tactically Quiet Generators (TQG's) into an improved layout in accordance with the army technical manual 3-34.46 (USAHQ 2013). This improved layout reallocates the generators to handle peak demand loads of the camp's infrastructure systems while maintaining realistic cable length and geometric arrangement constraints. By improving the generator layout, seven generators are eliminated from the power generation system, which reduces the overall total cost by $184,247. Furthermore, the daily fuel usage is reduced from 2,879 liters to 2,312 liters per day with the improved layout. When the cost preference weight is reduced to 0.8, the single large grid alternative is selected for the remainder of the scenarios. This TTP alternative utilizes grid technology to efficiently supply the required power to the camp while reducing the number of generators required from 24 to 10. The new TQG grid system reduces daily fuel usage from 2,879 liters to 1,519 liters per day. The fuel usage reduction of 1,359 liters is the largest saving of fuel usage in all the infrastructure categories. However, the added cost of this alternative is $234,899 more than the legacy power generation layout.

The subsistence infrastructure category produces rations for the camp through easily deployable infrastructure alternatives. The legacy system, an Expeditionary TRICON Kitchen Systems (ETK), is selected between the cost-weighted scenarios of 1.0 and 0.4. This legacy kitchen unit has an overall cost of $157,858, a fuel usage of 197 liters of fuel per day, and a potable water usage of 1,320 liters per day. The alternative is an updated ETK that uses a fuel-fired system. This alternative is selected when the cost performance weight is set from 0.3 to 0.0. The fuel-fired ETK has a reduced fuel usage of 191 liters per day with an added cost of $20,631. However, this alternative increases the potable water consumption to 1,332 liters per day.

Food and water refrigeration in a contingency environment is an essential camp function to sustain the population. The Multi-Temperature Refrigeration Container Systems (MTRCS) is a refrigeration unit that is highly transportable and deployable due to the system being contained in a standard-sized shipping container. This legacy system is selected between a cost preference of 1.0 to 0.1. When resource usage is prioritized with a weighted value of 1.0 and a cost-weighted value of 0.0, the combination alternative of a High-Efficiency MTRCS (HE-MTRCS) and solar array shade technology is selected. This alternative's fuel usage is 39.14 liters per day, which is a minimal reduction compared to the legacy equipment. However, the cost of this alternative combination is $57,113 more than the legacy MTRCS system. This alternative was selected in this weighted scenario because it reduces fuel usage compared to the baseline, even though it has a higher cost.

The water heating infrastructure category utilizes deployable technology to heat water for food preparation, laundry services, personal hygiene units, and latrine systems. This category's legacy equipment is a WH-400 water heating unit with Modern Burner Units (MBUs). This legacy system can supply all of the heated water for the 300-person camp with six units at a total cost of $153,482 while using 39.44 liters of fuel per day. The WH-400 and MBU system is selected at a cost-weighting scenario of 1.0 to 0.1 due to its minimal fuel usage and low cost compared to the alternative. When the weighting values are shifted to 1.0 on the performance scale, the alternative is selected. This alternative is a solar water heater system that requires 12 units to supply heated water to the 300-person camp at a total cost of $381,800, which is twice as much as the legacy system. The solar water heating units decrease the fuel usage by a minimal 0.3 liters but are selected due to reduced resource usage in this particular scenario.

The metering and monitoring category utilizes infrastructure equipment to analyze fuel usage and detect issues with the power generation system at the end-user level, in real-time. The baseline scenario did not use any metering and monitor systems. For the cost-weighted values of 1.0 to 0.8, no change is selected due to the high priority of minimizing cost. The infrastructure alternative in this case study is a Nonintrusive Load Monitoring System (NILM). This alternative can monitor essential characteristics of the fuel generation and distribution systems such as power usage, temperature, liquid levels, and pressure (Gillman 2014). The NILM system was selected from a cost-weighted value of 0.7 to 0.0. This alternative reduces fuel usage 27.18 per day with an added cost of $13,318. This system was selected over no monitoring technologies due to its potential to reduce overall fuel usage by 35% when properly calibrated and utilized to its full potential.

Self-serve laundry services are provided at the 300-personnel contingency bases. This infrastructure category consists of eight 20-pound commercial washers as the baseline equipment that make up 9% of the total potable water used on the camp. The alternative considered is a TTP, which reduces the amount of laundry a single person is allotted to do per week by half. This reduction aligns with the U.S. Army doctoral minimum for field conditions taken from the Water Planning Guide (US Army 2008). This TTP alternative is selected in every weighting scenario due to its reduction in water consumption and fuel usage. By implementing this TTP, the camp reduces its water usage from 2,971 liters to 2,844 liters per day when compared to the baseline of full laundry usage with no added costs.

Providing access to personal hygiene facilities consists of shower-shave units. This infrastructure category accounts for 63% of the potable water use on the contingency base, which translates to 20,802 liters per day. To reduce potable water resource usage, military planners can implement reduced shower times and low flow shower heads at the contingency base-level. The most inexpensive option is to reduce the shower time from 10 minutes to 5 minutes. This alternative TTP is selected when the cost-scenario was set to 1.0. The 5-minute shower TTP reduced the potable water usage by 26%, with a daily potable water usage of 15,484 liters. The combination alternative of 5-minute showers and low flow shower heads is selected for all other weighted scenarios. The combination of the TTP and new equipment reduced the overall potable water usage to 12,062 liters per day at a minimal added cost of $2,442 to procure and transport the new low flow shower heads.

The potable water production infrastructure category refers to the amount of water contingency bases utilize to conduct food preparation, laundry services, personal hygiene, and latrine services daily. This category excludes the daily amount of drinking water the base population requires. The baseline scenario utilized bulk potable water delivery via convoys from Bagram Airfield to contingency base Alpha and Bravo. This legacy contract was calculated to cost $25,907 to resupply the contingency base with 33,020 liters of potable water per day using Equation 6. The alternative, a Tactical Water Purification System (TWPS), is a highly deployable and versatile system that can produce potable water from a nearby non-potable water source at an overall cost of $253,088. The system can produce 5,678 liters of potable water per hour, which equates to five hours of operation to supply the full quantity of potable water required by the contingency base per day (Binggeli 2017). The optimization model selected the bulk potable water contract in every scenario due to the minimal initial purchase and set up costs and no added resource usage when compared to the TWPS option.

The latrine services infrastructure category consists of systems that collect, contain, and distribute solid and liquid waste. This infrastructure category accounts for 24% of the potable water usage at the contingency base level. The legacy system used in the baseline scenario is an Expeditionary Latrine System (ELS) with a total cost of $322,175 and utilizes 7,925 liters of potable water per day. When the cost-weighted scenario is set from 1.0 to 0.8, the chemical latrine alternative is selected due to its inexpensive costs to maintain, calculated at $21,946 for initial procurement and delivery.

This alternative also reduces the overall potable water usage by 564 liters per day. When the cost-weighted scenario is set from 0.7 to 0.0, the burnout latrine alternative is selected. Burn out latrines have a minimal total cost of $42,721 and a reduced potable water usage of 5,916 liters per day. This alternative reduces potable water usage 26% compared to the baseline, making it the most efficient resource reduction alternative in the latrine services infrastructure category.

The last two infrastructure categories are waste water management and solid waste management. The baseline mechanism to deal with these waste types is disposal contracts established with the local community. Due to the minimal costs and no added resource usage compared to the seven infrastructure alternatives, the optimization model selected the disposal contracts for each weighted scenario. However, if contracting services are unavailable, the black water recycler and solid waste destruction systems could serve as viable alternatives that balance an increase in cost and fuel usage.

Optimization Model Output Analysis: Contingency Base Bravo

Table 9 shows the optimization outputs for the varied weighting scenarios for contingency base Bravo. Contingency base Bravo has the same characteristics, planning factors, and environmental constraints as contingency base Alpha. However, contingency base Bravo is located 676 kilometers away from the MOB. The added travel distance of 241.5 kilometers compared to contingency base Alpha affects the initial delivery costs and resupply costs of the military planners' infrastructure options. Six of the 11 weighted scenarios produced unique results and are represented by the blue column heads. The weighted scenarios with cost values from 0.7 to 0.2 were all calculated to have the same infrastructure combinations. The following paragraphs will highlight the changes in infrastructure combinations at contingency base Bravo.

The first difference in infrastructure combinations at contingency base Bravo occurs in the subsistence infrastructure category. The legacy ETK system is selected in all weighted scenarios except when the performance weight is set to 1.0. The increased delivery and resupply costs of the alternative fuel-fired ETK cause the model to select the legacy equipment to minimize the overall operating cost at the farther contingency base.

The next deviation occurs in the personal hygiene category. For contingency base Bravo, the model selected the combination alternative of 5-minute showers and low flow shower heads for every weighted scenario. This is due to the minimal initial costs to procure the equipment and the potable water reduction provided by the TTP, making this alternative the most cost and performance effective at the given travel distance.

The final change in infrastructure combinations for contingency base Bravo occurs in the latrine services category. The chemical latrines alternative is selected for the weighted scenario of cost equal to 1.0 only due to the increased cost for initial delivery and potable water resupply. At contingency base Alpha, this alternative was selected for the cost-weighted scenarios of 1.0 to 0.8. The scenarios with a cost value of 0.9 to 0.0 select the burn-out latrine alternative.

Table 9: Optimization results for contingency base Bravo.

Infrastructure Group	Alt. Count	Infrastructure Alternative	Baseline Scenario	Cost=1 Res.=0	Cost=.9 Res.=.1	Cost=.8 Res.=.2	Cost=.7 Res.=.3	Cost=.6 Res.=.4	Cost=.5 Res.=.5	Cost=.4 Res.=.6	Cost=.3 Res.=.7	Cost=.2 Res.=.8	Cost=.1 Res.=.9	Cost=0 Res.=.1
A (Shelter)	1	AS TEMPER Tent	X											
	2	Liner-V1.5												
	3	Shade-ULCANS											X	
	4	Shade-PShade												
	5	V1.5 Liner & PShade												
	6	V1.5 Liner & ULCANS												X
	7	18 PAX per AS TEMPER Tent		X	X	X	X	X	X	X	X	X		
	8	Eliminate Convenience Loads												
B (Power Generation)	9	60kW Tactical Quiet Generator (TQG)	X											
	10	TM 3-34.46 Layout - 60kW TQGs		X	X									
	11	Hybrid Power Trailer (HPT)												
	12	T-100 (Towable Generator System)												
	13	Realistic Grid - 60kW TQGs												
	14	One Large Grid - 60kW TQGs				X	X	X	X	X	X	X	X	X
C (Subsistence)	15	Expiditionary TRICON Kitchen System (ETK)	X	X	X	X	X	X	X	X	X	X	X	
	16	Fuel-Fired ETK												X
D (Refrigeration)	17	Multi Temp. Refrigeration Container System (MTRCS)	X	X	X	X	X	X	X	X	X	X	X	
	18	High Efficiency MTRCS												
	19	High Efficiency MTRCS & Solar Array Shade												X
E (Water Heating)	20	WH-400 & Modern Burner Unit System (MBU)	X	X	X	X	X	X	X	X	X	X	X	
	21	Solar Water Heater System												X
F (Metering)	22	No metering/Monitoring	X	X	X	X								
	23	Nonintrusive Load Monitoring (NILM) System					X	X	X	X	X	X	X	X
G (Laundry Services)	24	20-lb commercial washers	X											
	25	1/2 Laundry Usage per week		X	X	X	X	X	X	X	X	X	X	X
H (Personal Hygiene Services)	26	10 Min Showers	X											
	27	5 Min Showers												
	28	Low Flow Shower Heads												
	29	5 Min Showers & Low Flow Shower Heads		X	X	X	X	X	X	X	X	X	X	X
I (Water Production)	30	Bulk Water Resupply	X	X	X	X	X	X	X	X	X	X	X	X
	31	Tactical Water Purificaiton System (TWPS)												
J (Latrine Services)	32	Expiditionary Latrine System (ELS)	X											
	33	ELS & Solid Waste Flush Only												
	34	ELS & Pipe Urninals												
	35	ELS & Waterless Urinals												
	36	Burn-Out Latrines			X	X	X	X	X	X	X	X	X	X
	37	Chemical Latrines		X										
	38	Low Cost TRICON Latrine System (LCTL)												
K (Waste Water Mngt.)	39	Bulk Waste Water Disposal	X	X	X	X	X	X	X	X	X	X	X	X
	40	Forward Osmosis/Reverse Osmosis Recycling (FORO)												
	41	Black Water Recycler												
	42	Deployable Baffled Bioreactor (DBBR)												
	43	FORO & DBBR												
L (Solid Waste Mngt.)	44	Bulk Solid Waste Disposal	X	X	X	X	X	X	X	X	X	X	X	X
	45	Open Air Burn Pit												
	46	Incinerator												
	47	Solid Waste Destruction System (SWDS)												

Cost Versus Performance Variables

This section analyzes the aforementioned infrastructure combinations for contingency base Alpha and Bravo to quantify and visualize cost and performance impacts over time. The optimized infrastructure combinations were simulated over four operational periods: 1-, 30-, 183-, and 365-days of operation. Figure 4, Figure 5, Figure 6, and Figure 7 visualizes the performance versus the total cost to procure, transport, resupply, and maintain contingency base Alpha at the specified weighted scenario over time. Additional non-optimized solutions were added for comparison and to assist in visualization of the Pareto front.

The baseline scenario is calculated to have a total cost of $1,917,617 and a performance value of 37,027 liters per day. Potable water usage makes up 33,020 liters of the total performance value, 89%, with fuel consumption making up the remaining 4,007 liters.

The weighted scenario of cost equal to 1.0 and performance weight of 0.0 is shown to have a decrease in cost and performance values, with the ultimate objective of minimizing costs. The total cost of this scenario was calculated to be $1,337,952, with a performance value of 30,432 liters per day. This scenario has a reduction in cost and performance values of $579,665 and 6.595 liters compared to the baseline scenario. This cost also represents the lowest initial cost of all of the infrastructure combinations. The most notable changes in this scenario are the TTP selection of the enhanced layout in accordance with TM 3-34.46 generator layout, five-minute shower, and an equipment change of chemical latrines. By selecting the TTP changes, a considerable reduction in cost can be realized due to the minimal changes in existing equipment.

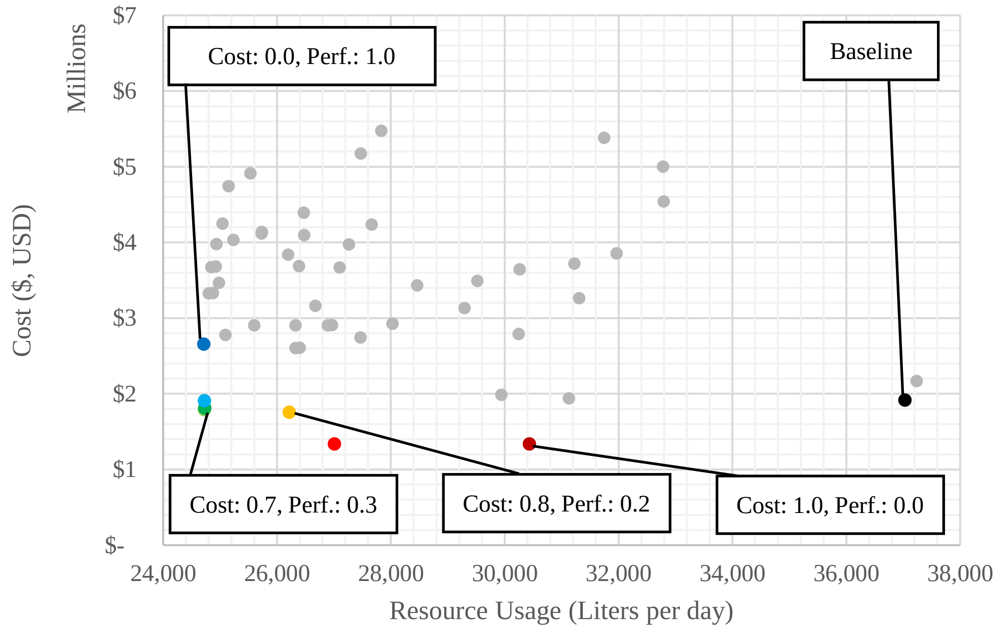


Figure 4: Cost versus performance of infrastructure combinations, initial operations, CB Alpha

The next scenario highlighted is at a cost weight of 0.8 and the performance weight of 0.2. The total cost and performance values were calculated to be $1,757,177 and 26,216 liters per day. This scenario has a reduced initial cost of $160,440 and a decrease in resource usage of 10,811 liters when compared to the baseline. The most notable change in this infrastructure combination is implementing one large generator grid system instead of the enhanced TM 3-34.46 generator layout.

The weighted scenario with a cost value of 0.7 and a performance value of 0.3 is highlighted next from Figure 4. This infrastructure combination has an initial cost of $1,791,218 and a performance value of 24,726 liters per day. Compared to the baseline scenario, this combination reduces the initial cost by $126,399 and reduces the resource usage by 12,301 liters. The most notable changes in this scenario are the deployment of burn-out latrines and the NILMS metering and monitoring systems. This infrastructure combination is selected between the cost weights of 0.7 to 0.4.

The objective of the scenario with cost weights of 0.0 and performance weight of 1.0 is to minimize the resource usage without concern for cost. The performance value was calculated to be 24,714 liters per day at an initial cost of $2,655,916. The reduction in resource usage is calculated to be 12,313 liters when compared to the baseline. The changes with the most influence on cost and performance outputs in this scenarios infrastructure combination are the selection of the (1) V1.5 liner and ULCANS shade in the shelter category, (2) the single large grid, (3) the Fuel-fired ETK, (4) Solar water heating system, (5) decreased laundry usage by half, and (6) the selection of burn out latrines. The largest reduction in resource usage can be achieved by selecting the most efficient infrastructure alternatives available in this study, with an added cost of $738,299 above the baseline costs.

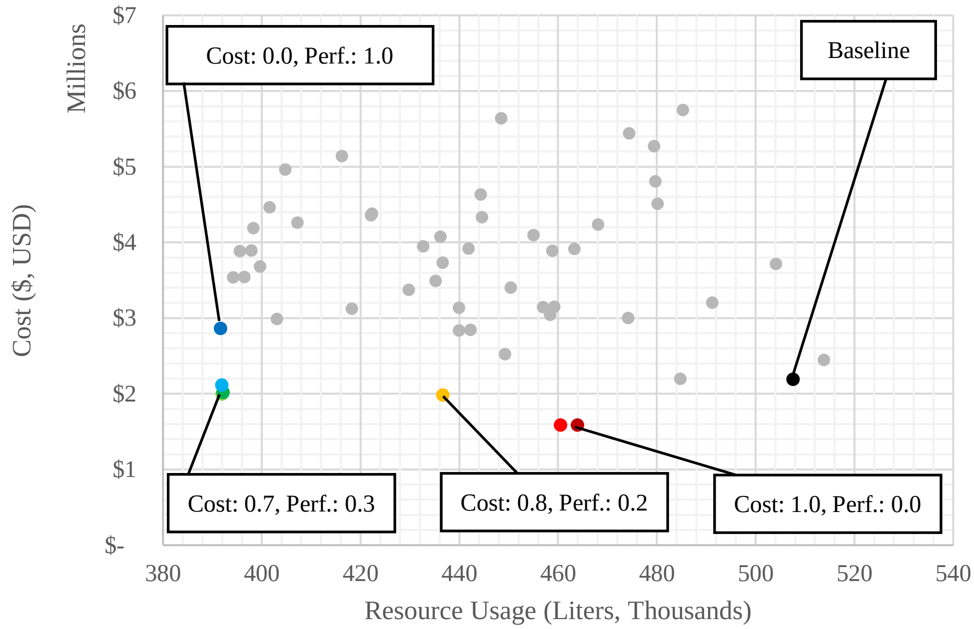


Figure 5: Cost versus performance of infrastructure combinations, 30 days of operation, CB Alpha

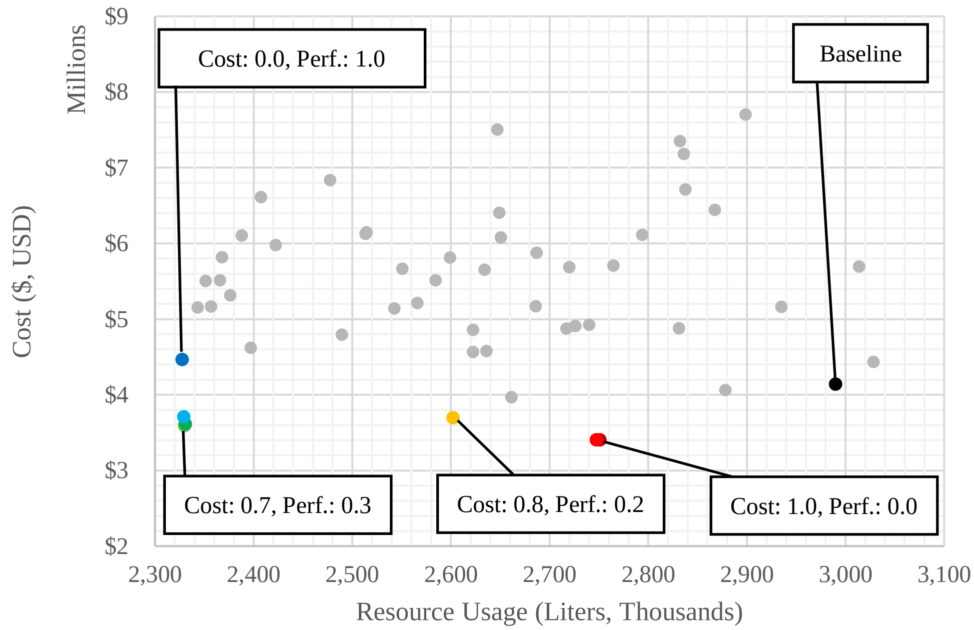


Figure 6: Cost versus performance of infrastructure combinations, 183 days of operation, CB Alpha

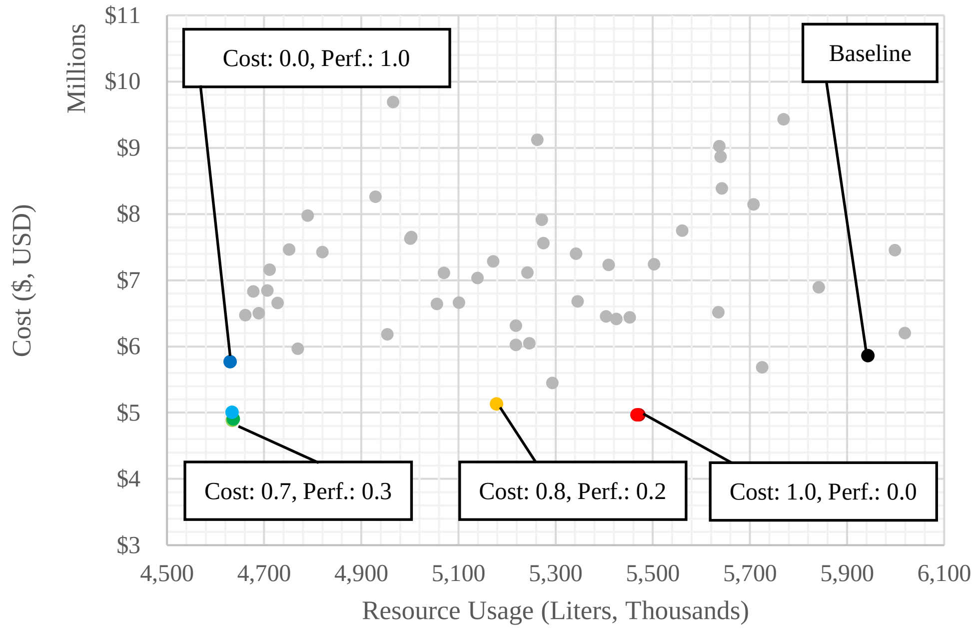


Figure 7: Cost versus performance of infrastructure combinations, 365 days of operation, CB Alpha

At the 365-day duration (Figure Figure 7), the baseline scenario has a total cost value of $5,362,502 and a performance value of 5,942,912 liters. The weighted scenario of cost equal to 1.0 has a cost value of $4,470,411 and a performance value of 5,471,610 liters. This scenario reduced the overall resource usage by 471,302 liters per year while also reducing the cost by $892,091. This large reduction in performance values signifies that TTP changes can drastically reduce resource usage at the contingency base level while reducing overall cost.

The weighted scenario of cost equal to 0.8 and performance equal to 0.2 has a monetary value of $4,635,122 and a performance value of 5,178,160 liters. At the weighted scenario of cost equal to 0.7 and performance equal to 0.3, the cost value is calculated to be $4,386,916 and a performance value of 4,634,646 liters. This solution represents a balanced infrastructure combination with the objectives of minimizing cost and performance values by selecting a unique combination of TTP and infrastructure alternatives. The final scenario to highlight has a performance value of 1.0 and a weighted cost value of 0.0. This scenario's total cost is calculated to be $5,271,094, which is only $91,408 less than the baseline scenario. However, this scenario has the lowest resource usage of all the infrastructure combinations with 4,630,246 liters over the 365-days of operation. Contingency base Bravo has very similar results across the weighted scenarios when compared to non-optimized solutions. The longer travel distance increases the overall costs of the solutions, but the resource usage is constant. The cost versus performance figures for contingency base Bravo are located in the Appendix.

Resource Performance Analysis

This section analyzes the weighted scenarios' resource performance over time with varying infrastructure combinations at both contingency base Alpha and Bravo. Figure 8 shows the combined fuel and potable water resource usage from initial setup to 365 days of operation at contingency base Alpha. Resource performance is linear across the weighted scenarios at both contingency bases, which allows the military planner to project resource usage over a specified operational duration.

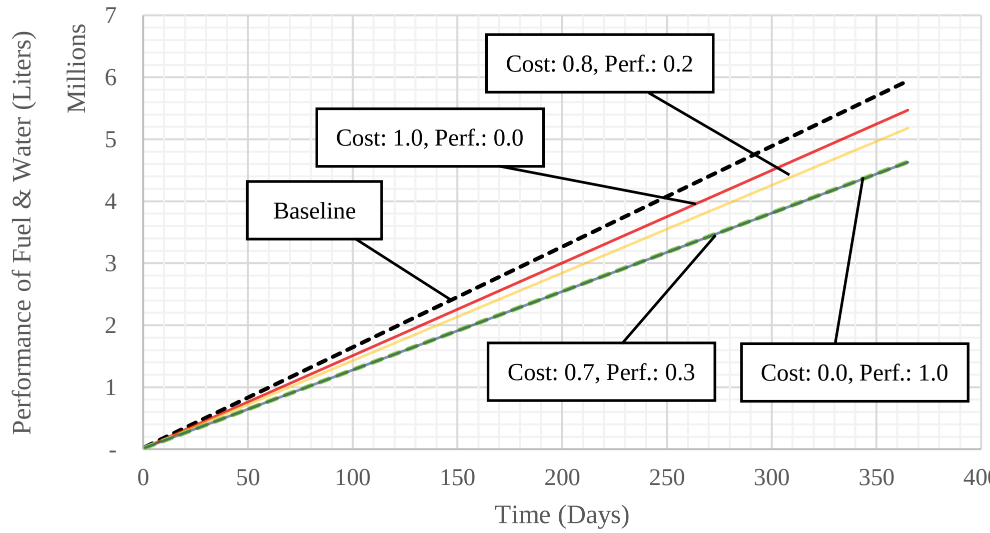


Figure 8: Optimized resource usage over 365 days at CB Alpha.

From Figure 8, it can be extracted that the baseline scenario has the highest resource usage of all the scenarios with a performance value of 5,942,912 liters over 365-days of operation. The weighted scenario with a cost value of 0.0 and a performance value of 1.0, represented by the dashed blue line on the lower bound, has the lowest overall resource usage value at 4,630,246 liters annually, which reduces 1,312,666 liters compared to the baseline. This scenario signifies the lowest overall resource usage possible. From a cost value of 0.7 to 0.0, the resource usage is reduced by smaller increments, causing overlap in Figure 8at the lower bound. Table 10 highlights the performance values of the unique weighted scenarios at contingency base Alpha after 365 days of operation.

Table 10: Optimized resource usage over time at CB Alpha over 365 days of operaiton.

365 Days of Operation		Baseline Scenario	Cost = 1.0 Perf. = 0.0	Cost = 0.9 Perf. = 0.1	Cost = 0.8 Perf. = 0.2	Cost = 0.7 Perf. = 0.3	Cost = 0.3 Perf. = 0.7	Cost = 0.1 Perf. = 0.9	Cost = 0.0 Perf. = 1.0
CB Alpha	Fuel Usage (Liters)	1,462,740	1,250,308	1,249,755	960,280	943,018	940,807	937,906	934,418
	Potable Water (Liters)	4,480,171	4,221,302	4,217,880	4,217,880	3,691,628	3,695,828	3,695,828	3,695,828
	Total Resource Usage	5,942,912	5,471,610	5,467,635	5,178,160	4,634,646	4,636,635	4,633,734	4,630,246

Table 11 visualizes the number of resupply trucks required to replenish the fuel and potable water supply at contingency base Alpha over a 365-day operational period. All fractions of resupply trucks were rounded up to account for the actual amount of resupply vehicles required to resupply the contingency bases at the given time interval.

Table 11: CB Alpha resupply trucks required at 365 days of operation.

365 Days of Operation	Baseline Scenario	Cost = 1.0 Perf. = 0.0	Cost = 0.9 Perf. = 0.1	Cost = 0.8 Perf. = 0.2	Cost = 0.7 Perf. = 0.3	Cost = 0.3 Perf. = 0.7	Cost = 0.1 Perf. = 0.9	Cost = 0.0 Perf. = 1.0
Fuel Trucks Required	77	66	66	51	50	50	50	49
Potable Water Trucks Required	296	279	279	279	244	244	244	244
Total Trucks Required	373	345	345	329	294	294	294	293

The bulk fuel transportation vehicles have a capacity of 18,927 liters, while the potable water vehicles have a capacity of 15,141 liters. From Table 11, the baseline scenario requires a total of 373 trucks over a one-year period to resupply fuel and potable water at contingency base Alpha. At the weighted scenario of cost equal to 1.0 and performance equal to 0.0, the number of fuel trucks required is reduced to 345. As the scenarios shift from minimizing cost to minimizing performance, the number of trucks needed for resupply continues to decrease. At the weighted scenario of cost equal to 0.0 and performance equal to 1.0, the number of resupply trucks is fully minimized at 293 over the one-year operational period. This scenario reduces the resupply trucks by 80 when compared to the baseline scenario.

As seen in Table 9, the increased distance from the MOB drives the model to select different infrastructure combinations for contingency base Bravo. Figure 9 shows the performance values at contingency base Bravo over the 365-day operational duration. The weighted scenario with a cost value of 1.0 has a resource performance value of 5,468,813 annually, 474,099 liters less than the baseline and 2,797 liters less than the same weighted scenario for contingency base Alpha.

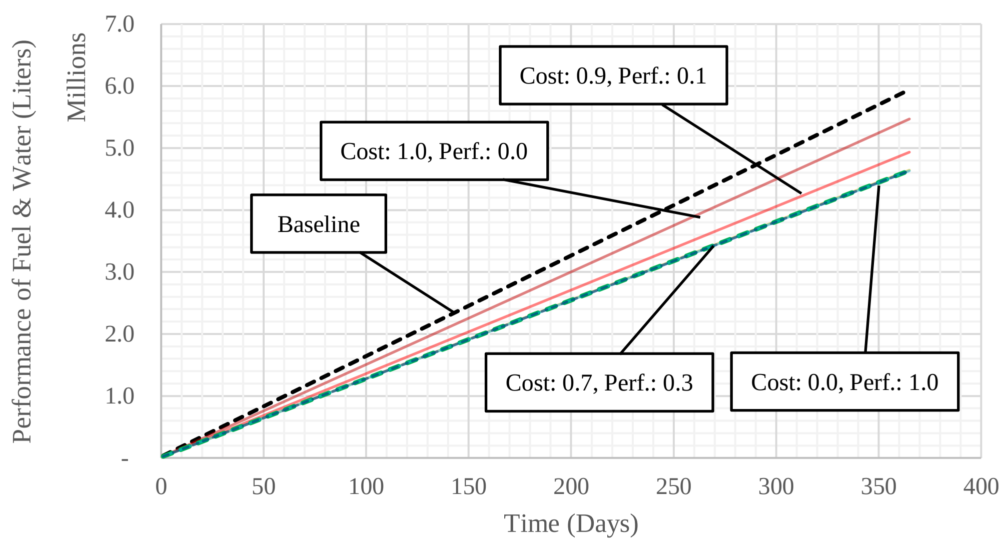


Figure 9: Optimized resource usage over 365 days at CB Bravo.

From a cost value of 0.8 to 0.0, the resource usage is reduced by smaller increments, causing overlap in Figure 9 at the lower bound above the lowest resource usage with a cost value of 0.0 and performance value of 1.0. Due to the added travel distance of contingency base Bravo, the model selected infrastructure combinations that reduce resource usage at a higher cost-weighted scenario than contingency base Alpha's optimized solutions. Table 12 visualizes the total resource usage values of fuel and potable water at contingency base Bravo over the 365-day operational period.

Table 12: Optimized resource usage at CB Bravo over 365 days of operation.

365 Days of Operation		Baseline Scenario	Cost = 1.0 Perf. = 0.0	Cost = 0.9 Perf. = 0.1	Cost = 0.8 Perf. = 0.2	Cost = 0.7 Perf. = 0.3	Cost = 0.3 Perf. = 0.7	Cost = 0.1 Perf. = 0.9	Cost = 0.0 Perf. = 1.0
CB Alpha	Fuel Usage (Liters)	1,462,740	1,250,930	1,241,935	952,460	944,192	944,192	941,291	936,720
	Potable Water (Liters)	4,480,171	4,217,883	3,691,631	3,691,631	3,691,631	3,691,631	3,691,631	3,695,831
	Total Resource Usage	5,942,912	5,468,813	4,933,566	4,644,091	4,635,823	4,635,823	4,632,922	4,632,551

Table 13 shows the resupply trucks required for contingency base Bravo over the one-year operational period. At the weighted scenario of cost equal to 0.9 and performance equal to 0.1, the added distance and unique infrastructure combination are seen to reduce the truck count by 64 trucks when compared to the baseline scenario, and 36 trucks when compared to the same weighted scenario at contingency base Alpha.

Table 13: CB Bravo resupply trucks required at 365 days of operation.

365 Days of Operation	Baseline Scenario	Cost = 1.0 Perf. = 0.0	Cost = 0.9 Perf. = 0.1	Cost = 0.8 Perf. = 0.2	Cost = 0.7 Perf. = 0.3	Cost = 0.3 Perf. = 0.7	Cost = 0.1 Perf. = 0.9	Cost = 0.0 Perf. = 1.0
Fuel Trucks Required	77	66	66	50	50	50	50	49
Potable Water Trucks Required	296	279	244	244	244	244	244	244
Total Trucks Required	373	345	309	294	294	294	294	293

At both contingency bases, potable water usage is the largest resource used in terms of volume, making up roughly 80% of the performance value. Potable water has a lower overall fully burdened cost per liter. Still, the water volume required for resupply is larger than the fuel volume required, making potable water a controlling resource in the combined resource equation. Targeting a reduction in potable water usage at the contingency-base level will have the largest reduction in sustainment costs over long operational durations. The model also shows that it can account for varied resupply costs due to travel distance, which alters the infrastructure selected for a contingency base.

Sustainment Costs Analysis

This section examines the sustainment costs of a contingency base over an extended operational duration. Initial costs include delivery and procurement, while sustainment costs are comprised of maintenance and resupply of essential resources such as fuel and potable water. The procurement and delivery costs are one-time payments that occur upon initial deployment of the selected infrastructure combination to the contingency base. Following initial deployment and setup, daily sustainment costs for maintenance and resupply are incurred. Figure 10 visualizes how the total sustainment costs are incurred at contingency base Alpha over a six-year operational duration.

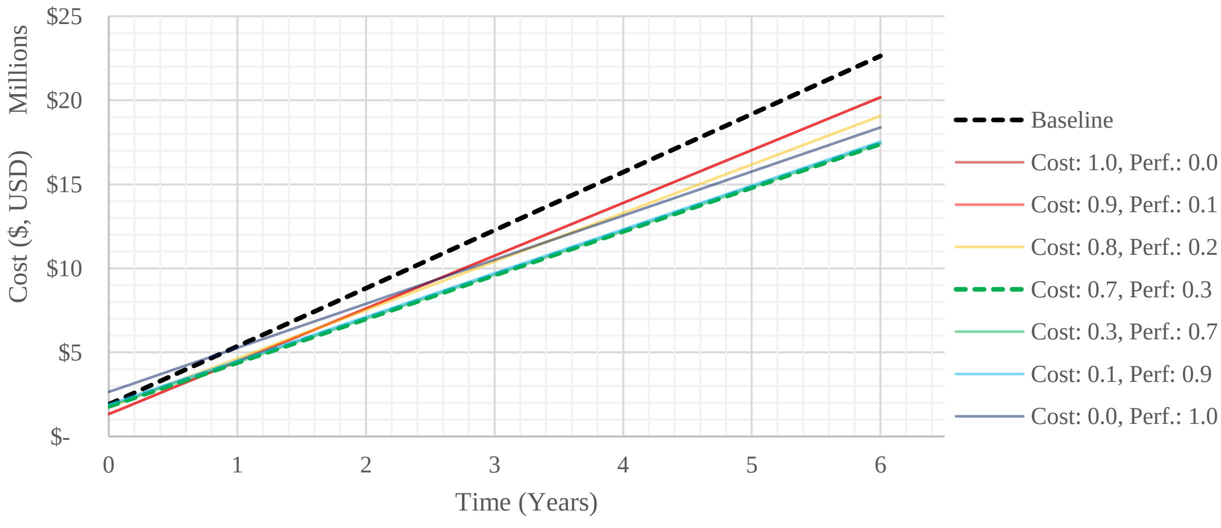


Figure 10: Total cost of CB Alpha over a six-year operational duration.

Figure 10 shows the total costs of the baseline scenario and the weighted scenarios with varied infrastructure combinations. The baseline scenario has an initial cost of $1,940,623 with a reoccurring maintenance and resupply cost of $19,682 per day. As time progresses, the baseline scenario can be seen to emerge as the most expensive infrastructure combination. The weighted scenario with a cost value of 1.0 and a performance value of 0.0 has the lowest overall initial cost with a value of $1,337,952 and a daily sustainment cost of $16,212. As operations continue, this scenario, which is intended to minimize costs, becomes the second most costly infrastructure combination to sustain at the 2.5-year mark. The cost-weighted scenario of 0.9 has a similar path as the fully minimized cost infrastructure combination, leveling out as the third highest sustainment cost. Due to the high sustainment costs, these weighted scenarios are not likely to be selected by military planners for extended operational durations.

The weighted scenario of cost equal to 0.0 and performance value equal to 1.0 has the highest initial cost to procure and deliver at $2,655,916, which is 28% more than the initial cost of the baseline scenario. However, with a daily sustainment cost of $13,110, this scenario can be seen to cross the baseline scenario at the 1-year mark on the downward linear trend to become the third-lowest cost scenario to sustain.

The cost-weighted scenarios with values from 0.8 to 0.1 (performance values of 0.2 to 0.9, respectively) congregate between the $1.9 million and $1.7 million initial cost range and are very competitive throughout the duration of operations. Further analysis shows the weighted scenario of cost equal to 0.7 and a performance value equal to 0.3 emerges as the lowest sustainment cost of all the weighted scenarios at the one-year mark. This infrastructure combination is calculated to have an initial procurement and set up cost of $1,791218, saving $126,399 compared to the baseline scenario. The daily sustainment cost is calculated to be $13,056, which saves $6,626 compared to the baseline scenario. At six years of operation the optimized infrastructure combination is calculated to reduce resource usage by 2,805,895 liters of fuel and potable water, amounting to $4,557,816 in savings compared to the baseline scenario. Resupply trucks are also reduced by 474 vehicles on the road over a six-year operational period when compared to the baseline. The cost and performance values of this scenario can be seen in Table 14. This infrastructure combination signifies a balanced solution to minimize cost and performance over a set operational duration.

Table 14: Balanced weighted scenario for contingency base Alpha

Cost = 0.7, Perfromance = 0.3						
Costs	Duration (Days)	1	30	183	365	2,190
	Procurement & Delivery	$1,778,162	$1,778,162	$1,778,162	$1,778,162	$1,778,162
	Maintenance	$311	$9,319	$56,848	$113,385	$680,313
Fuel	Resources Usage (Liters)	2584	77508	472801	943018	5658107
	Resupply Trucks	0	4	25	50	299
	Resupply Cost	$1,869	$56,056	$341,940	$682,011	$4,092,065
Potable Water	Resources Usage (Liters)	22143	314492	1856886	3691628	22089455
	Resupply Trucks	1	21	123	244	1459
	Resupply Cost	$10,877	$154,481	$912,118	$1,813,358	$10,850,525
Totals	Total Cost	$1,791,218	$1,998,018	$3,089,067	$4,386,916	$17,401,064
	Total Resource Usage	24727	392001	2329686	4634646	27747562
	Reoccuring Costs	$13,056	$219,856	$1,310,905	$2,608,755	$15,622,902

Contingency base Bravo has the same characteristics, planning factors, and operational duration as contingency base Alpha, except for an extended travel distance from the main operating base. The added 241.5 kilometers affects the initial cost of delivery and the cost of resupply, driving the optimization model to adjust the infrastructure selections across the weighted scenarios. Figure 11 shows the total cost of contingency base Bravo at six-years of operation.

Similar to contingency base Alpha, the baseline scenario persists as the highest cost alternative over the six years of operation and the second-highest cost to procure and deliver. This scenario surpassed the cost weighted scenario with a value of 0.0 at the one-year mark. The weighted scenarios with cost values from 1.0 to 0.9 are consistent in having the lowest overall initial procurement and delivery cost but have the second and third highest costs in terms of sustainment.

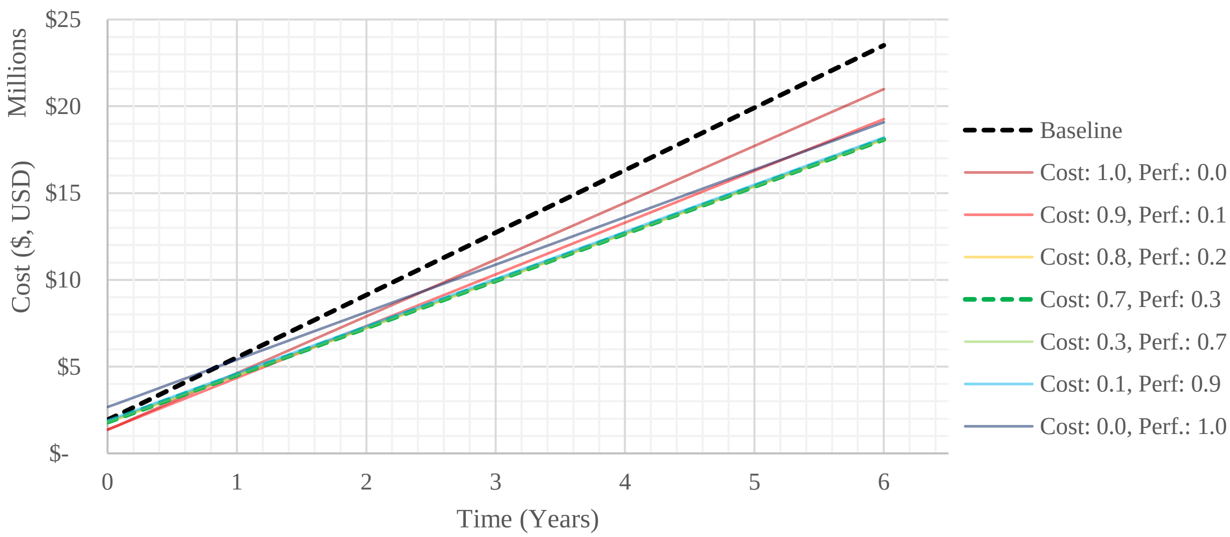


Figure 11: Total cost of CB Bravo over a six-year operational duration.

The weighted scenarios with cost values between 0.8 and 0.1 follow a similar linear trend throughout the six-year operational duration, congregating on the lower bound. Further analysis shows that the weighted scenario with a cost value of 0.7 is again the lowest cost infrastructure combination. This scenario has a cost value equal to 0.7 and a performance value of 0.3 has an initial cost of $1,791,218, which saves $136,708 compared to the baseline scenario. At one year of operation, this scenario emerges as the lowest cost scenario to sustain with a daily value of $13,667, which is $6,924 less than the baseline scenario. At six-years of operations, this scenario has a resource usage of 27,754,611 liters. Compared to the baseline, this scenario uses 7,798,845 liters less of fuel and potable water, amounting to a savings of $4,736,713. Additionally, 474 resupply trucks are eliminated with this infrastructure combination over the six-year period compared to the baseline infrastructure combination. This weighted scenario represents the most balanced infrastructure combination to minimize cost and performance at contingency base Bravo. Table 15 visualizes the cost and performance parameters calculated for contingency base Bravo over the full operational duration.

Table 15: Balanced weighted scenario for contingency base Bravo.

Cost = 0.7, Perfromance = 0.3						
Costs	Duration (Days)	1	30	183	365	2,190
	Procurement & Delivery	$1,790,248	$1,790,248	$1,790,248	$1,790,248	$1,790,248
	Maintenance	$311	$9,319	$56,848	$113,385	$680,313
Fuel	Resources Usage (Liters)	2587	77605	473390	944192	5665153
	Resupply Trucks	0	4	25	50	299
	Resupply Cost	$1,927	$57,808	$352,626	$703,326	$4,219,955
Potable Water	Resources Usage (Liters)	22147	314496	1856889	3691631	22089458
	Resupply Trucks	1	21	123	244	1459
	Resupply Cost	$11,429	$162,303	$958,291	$1,905,153	$11,399,785
Totals	Total Cost	$1,803,915	$2,019,678	$3,158,014	$4,512,113	$18,090,301
	Total Resource Usage	24733	392100	2330278	4635823	27754611
	Reoccuring Costs	$13,667	$229,430	$1,367,766	$2,721,864	$16,300,053

Summary

This chapter demonstrated the optimization model's capabilities to select varied infrastructure combinations based on military planner’s priorities, with the ultimate objectives of minimizing cost and performance. The model was applied to a hypothetical case study involving two 300-person contingency base in a desert environment with varying delivery route distances from a main operating base in a hub-and-spoke network. Cost and performance weights were varied across the optimization process to produce 11 optimized solutions for both contingency bases, resulting in 22 optimized solutions. Contingency base Alpha had seven unique solutions, while contingency base bravo had six unique solutions.

At contingency base Alpha and Bravo, the most impactful infrastructure alternative changes involve the power production and the latrine systems infrastructure categories. The deployment of a single grid power production system was calculated to use 1,520 liters of fuel per day, 48% less than the legacy power production infrastructure currently deployed at contingency bases. This technology has the potential to save 496,242 liters of fuel per year at a 300-person contingency base compared to the legacy 60 kW generator layout. This decrease in fuel usage also reduces the resupply cost by $369,649 per year and resupply vehicles on the road by 27. The burn-out latrines have the potential to save 193,683 liters of potable water usage per year, amounting to $378,371 savings in resupply costs. TTPs also have the potential to minimize cost and resource usage with no additional equipment. By reducing laundry usage of personnel to half per week, the potable water usage can be reduced by 12,319 liters per year, saving $24,065 in resupply costs. The most impactful infrastructure combinations include a synergistic selection of equipment and TTPs working together to minimize the cost and resource usage at the contingency base level.

Further analysis was conducted on the cost and performance variables a six-year operational duration. This analysis shows that attempting to fully minimize the cost of an infrastructure combination does not produce the optimal results over time. Instead, a balanced approach, as seen in the weighted scenario with cost equal to 0.7 and performance equal to 0.3, has the lowest overall cost over time while drastically reducing the resource usage at the contingency base level.

Another critical inference from this analysis is that minimizing potable water usage has a larger effect on performance and reoccurring costs than fuel usage. Potable water accounts for roughly 80% of the total resource usage at contingency bases in this study. The costs to transport and deliver potable water are less per liter than the fuel cost, but the variation in vehicle transportation capacities and the sheer volume of usage make potable water a dominant resource in the combined resource equation.

In this analysis, the weighted scenario with a cost value of 0.7 and a performance value of 0.3 proved to be the optimal solution for both contingency base Alpha and Bravo. The cost savings potential is calculated to be $136,708 at initial procurement and delivery, while the resupply cost savings is $793,210 per year at contingency base Bravo. The combined resource usage is calculated to be 4,635,823 liters per year, which is a resource reduction of 22% compared to the baseline scenario. This reduction in resource usage eliminates 80 resupply trucks traveling on the road per year in hostile environments within the hub-and-spoke network.

V. Conclusions

Introduction

The purpose of this chapter is to summarize the goals and objectives of this study from Chapter 1. The next section will highlight key findings from the results and analysis of this research from Chapter 4. Following the key findings, the expected research contributions and technical significance of this thesis will be discussed. Next, the limitations of this study will be outlined and explained in detail. Finally, recommendations for future research in this study area will be described.

Research Summary

This study intended to develop an optimization model capable of selecting infrastructure combinations that balance tradeoffs between cost and performance at multiple contingency bases within a hub-and-spoke network. To that end, the study aimed to accomplish the following research objectives:

1. Execute a comprehensive review of the current body of literature pertaining to the sustainability practices, techniques, and optimization methods related to contingency base infrastructure.
2. Identify and quantify tradeoffs between infrastructure alternative performance and alternative costs of deployment, sustainment, and resupply at the contingency base level.

3. Develop an optimization model capable of balancing tradeoffs between infrastructure alternative performance and economic performance at multiple contingency bases within a military logistical supply network.

A comprehensive literature review was accomplished to understand the current state of literature around three main areas. The first focus area encompassed current infrastructure alternative optimization techniques at the equipment level. The second focus area reviewed literature that performed optimization modeling at the contingency base level. The final focus area examined contingency base characteristics, classifications, and planning factors. From this review, a literature gap was identified. This research aimed to fill the gap focused on minimizing the cost and performance of infrastructure combinations at multiple contingency bases within a hub-and-spoke network.

To address the aforementioned literature gap, an optimization model was developed to optimize infrastructure combinations at the contingency base level by minimizing the costs and performance variables. This model considers varying infrastructure alternatives within key infrastructure categories required for contingency base sustainment. Weighted cost and performance variables were used to represent the military planners' priorities. The model accounts for costs associated with procurement, initial delivery, maintenance, and resupply, along with infrastructure alternative fuel and potable water usage.

To evaluate this model's capabilities, a case study was designed that included two contingency bases and a main operating base within a hub-and-spoke network. The results demonstrate that the model can select varied infrastructure combinations that balance tradeoffs between infrastructure alternatives costs, resource usage, and military planners' priorities. The model is also capable of varying infrastructure selections when the resupply distance varies between the main operating base and the contingency base.

Key Findings

The first key finding from this research is at the infrastructure component level. Infrastructure alternatives perform vital functions within their infrastructure categories and have varied costs and resource usages. The most impactful infrastructure alternatives have the largest effects on fuel and potable water usage. The power production infrastructure category accounts for 73% of the fuel usage on the camp. The deployment of a single large grid reduces fuel usage by 47% compared to the legacy alternative. The latrine systems infrastructure category has the largest impact on potable water usage. The legacy system uses 764,134 liters annually. To combat this large resource usage, the deployment of burn-out latrines reduces potable water usage by 26%.

The selection of an efficient infrastructure combination includes equipment and TTP alternatives. Equipment alternatives affect both the cost and resource usage variables. These alternatives often have a higher initial procurement and delivery cost than legacy equipment. However, this equipment often performs the camp function more efficiently, reducing resource usage and sustainment costs. By implementing TTPs at the contingency-base level, military planners can substantially reduce resource usage with little to no added cost.

This study focused on reducing the fuel and potable water usage of infrastructure combinations at contingency bases within a network. At any operational duration, the extensive resource usage of potable water proves to be a controlling variable in the combined resource usage equation. The potable water daily requirement and the variation in resupply vehicle capacities outweigh the fuel requirements and resupply costs, even though the fully burdened cost of fuel is higher than that of potable water. The military planners' priorities when minimizing resource usage should target potable water use over fuel use to reduce overall sustainment costs during the operational duration.

A balanced infrastructure combination successfully weighs the tradeoff between minimizing costs and minimizing performance. This study found that minimizing costs over performance does not translate to the most efficient infrastructure combination over an operational duration. Higher savings can be realized by selecting a balanced solution that accounts for both cost and performance variables. The weighed scenario with a cost value of 0.7 and a performance value of 0.3 proved to be the most well-balanced solutions for both contingency base Alpha and Bravo. The reduced procurement and initial delivery costs along with a minimized daily sustainment cost demonstrated to be the most efficient infrastructure combination over a six-year operational duration.

Research Contributions

This research developed an optimization model capable of balancing tradeoffs between minimizing costs and performance of contingency base infrastructure combinations over a projected operational duration within a network. By accounting for cost and performance metrics, military planners can add, remove or adjust alternatives for consideration in the optimization selection database. The model is easily adapted to an established or projected AOR with multiple contingency bases at varying distances. Military planners can use this tool to select unique infrastructure combinations for each camp within a network, with the ultimate goal of producing more self-sufficient and sustainable contingency bases. The adjustment of cost and performance variables also allows real-world data to be input to produce a highly realistic infrastructure system.

Research Significance

This study adapted established optimization techniques to select optimal infrastructure combinations at multiple contingency bases simultaneously. The development of the model allows for the input of numerous cost and performance criteria, along with operational duration constraints and resupply route distances. By performing the optimization on multiple contingency bases simultaneously, the military planner can analyze an entire military supply network instead of one contingency base at a time. The objective function allows for variation in military planner's priorities with weighted criteria for the cost and performance variables. This unique capability enables optimizations to be conducted to produce varied selections of infrastructure combinations.

Research Limitations

The first limitation of this research is the cost data. Consistent cost data such as procurement and daily maintenance costs for new and existing technologies is hard to obtain. The cost data for infrastructure alternatives might not be quantified or thoroughly tested at the time of this research, driving the need to make educated assumptions for cost values. The main cost variables impacted by this limitation are the maintenance costs associated with the infrastructure alternatives.

The use of the Simplex LP solver function in Microsoft Excel's Solver program is another limitation in this research. The model can only solve for multiple contingency base infrastructure combinations with a single weighted preference at a time. However, more robust software could perform all of the weighted scenarios in a single simulation and provide detailed output statistics without further data interpretation.

The next limitation of this study is the focus on fuel and potable water resources use only. Contingency bases require fuel and potable water for sustainment, but they also produce solid and liquid waste. The model's boundary only considered material and resources coming into the camp and neglects materials and resources leaving the camp. Waste generation and disposal is an integral part of the sustainment equation. However, this study only includes fuel and potable water resources in the optimization objectives.

Another limitation of this research is the assumption that resupply vehicles and resupply resources are not limited within the network. The model does not account for the possibility of the number of vehicles available to resupply the bases. The model also does not consider limited fuel and potable water supplies available for resupply at the main operating base.

The model is also limited because it only selects a single alternative within each category to provide a single service. A combination of infrastructure alternatives can be deployed within a single infrastructure category. This limitation, if accounted for could add further customization options for each contingency base within a network.

The final limitation is that the resupply process was limited to ground operations only. Contingency bases can be resupplied by ground, air, and in some cases, sea. By only considering one avenue of resupply, the model is limited in its capabilities to select other efficient resupply options. However, ground resupply and logistics make up a large portion of the resupply network costs and operations. Additional contingency base characteristics would need to be considered to enable the addition of other resupply methods, such as runway characteristics, base coverage for drop zone areas, aircraft refueling capabilities, and the threat to air assets in the region.

Recommendations for Future Research

This section outlines recommended future areas that can be explored from the development of this study. The first recommended area of research is the development of a more extensive hub-and-spoke network. The model can be adapted to include more than two contingency bases at varying distances from multiple main operating bases. A full network analysis can be performed by adding more contingency and main operating bases with varying distances.

Another future research area could include the addition of multiple supply routes to contingency bases. Multiple supply routes would allow for logistical network optimizations in conjunction with infrastructure combination optimizations to be performed. A hostile threat variable could be included with the varied supply routes to add a human cost factor to the model.

Expanding the delivery vehicles for initial delivery and resupply is another focus area that could help create a realistic network. Resupply of essential resources by military air assets or supply drop are viable delivery methods currently used in hostile environments. Multiple resupply methods would expand the scope of the possible optimal solutions within the hub-and-spoke network.

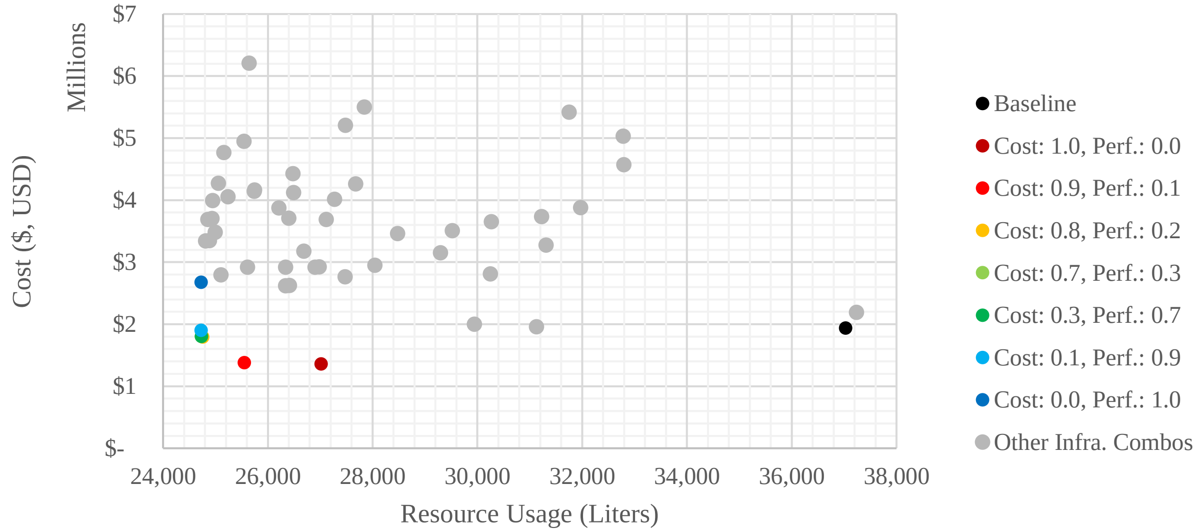
Another overlooked variable is the quality of life due to living conditions at the contingency base level. Operationally, an alternative could have an overall low cost to sustain or reduce the resource usage dramatically; however, the alternative may impact the quality of life of the personnel on the base and have a large detrimental effect on the surrounding environment. The model could be adapted to minimize the environmental impacts produced by the infrastructure combination. Additionally, the model could be modified to maximize the quality of life associated with the deployment of an infrastructure alternative combination.

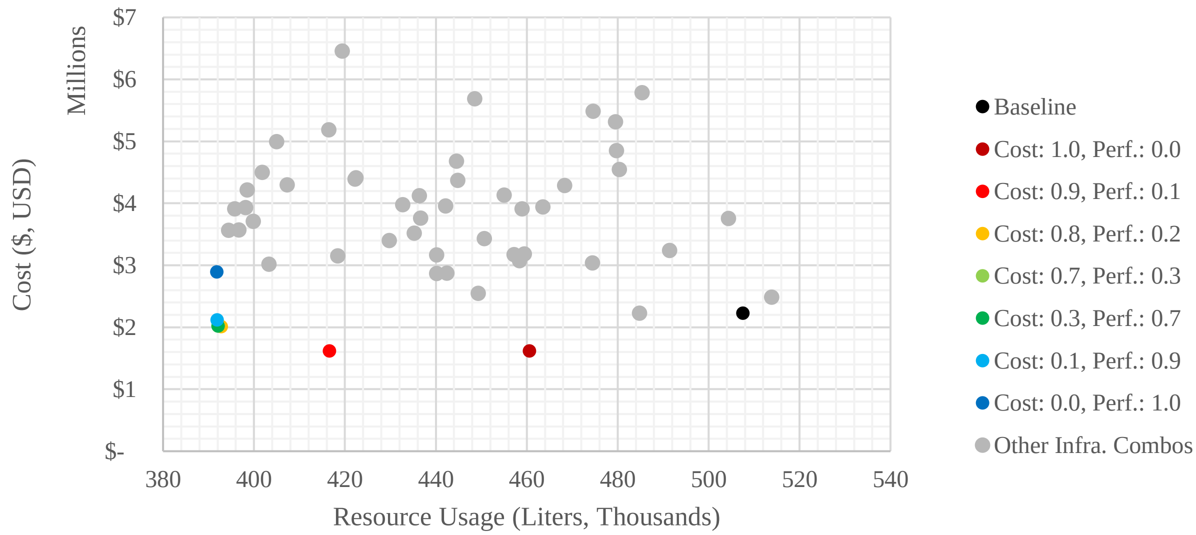
Appendix

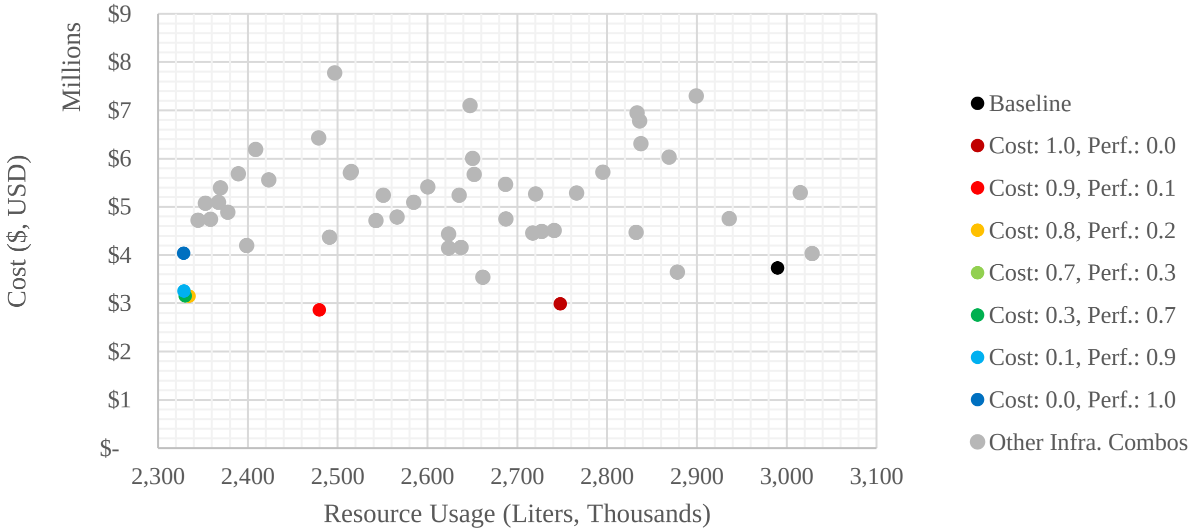
Case study infrastructure alternatives database at initial setup, contingency base Bravo.

Infrastructre Group	Alt. Count	Infrastructure Alternative	Alt. Type	Equip. Count	Total Cost	Fuel Usage (liters)	Potable Water Usage (liters)
A (Shelter)	1	AS TEMPER Tent	Equipment	23	$ 426,859	237	-
	2	Liner-V1.5	Equipment	23	$ 464,454	215	-
	3	Shade-ULCANS	Equipment	23	$ 429,844	216	-
	4	Shade-PShade	Equipment	23	$ 571,993	223	-
	5	V1.5 Liner & PShade	Equipment	23	$1,035,132	214	-
	6	V1.5 Liner & ULCANS	Equipment	23	$ 892,985	207	-
	7	18 PAX per AS TEMPER Tent	TTP	18	$ 334,347	224	-
	8	Eliminate Convenience Loads	TTP	23	$ 426,862	232	-
B (Power Generation)	9	60kW Tactical Quiet Generator (TQG)	Equipment	24	$ 642,126	2,879	-
	10	TM 3-34.46 Layout - 60kW TQGs	TTP	17	$ 455,378	2,313	-
	11	Hybrid Power Trailer (HPT)	Equipment	24	$2,306,999	2,001	-
	12	T-100 (Towable Generator System)	Equipment	24	$1,950,548	2,512	-
	13	Realistic Grid - 60kW TQGs	Equipment	14	$ 795,065	1,697	-
	14	One Large Grid - 60kW TQGs	Equipment	10	$ 868,461	1,520	-
C (Subsistence)	15	Expiditionary TRICON Kitchen System (ETK)	Equipment	2	$ 158,305	197	1,321
	16	Fuel-Fired ETK	Equipment	2	$ 178,937	191	1,332
D (Refrigeration)	17	Multi Temp. Refrigeration Container System	Equipment	4	$ 185,339	39	-
	18	High Efficiency MTRCS	Equipment	4	$ 193,326	39	-
	19	High Efficiency MTRCS & Solar Array Shade	Equipment	4	$ 242,772	39	-
E (Water Heating)	20	WH-400 & Modern Burner Unit System (MBU)	Equipment	6	$ 153,893	39	-
	21	Solar Water Heater System	Equipment	12	$ 388,211	39	-
F (Metering)	22	No metering/Monitoring	N/A	6	$ 1,196	76	-
	23	Nonintrusive Load Monitoring (NILM) & Deployable	Equipment	6	$ 13,723	49	-
G (Laundry Services)	24	20-lb commercial washers	Equipment	8	$ 9,880	79	2,972
	25	1/2 Laundry Usage per week	TTP	8	$ 9,814	78	2,844
H (Personal Hygiene Services)	26	10 Min Showers	TTP	0	$ 12,031	197	20,803
	27	5 Min Showers	TTP	0	$ 9,285	195	15,485
	28	Low Flow Shower Heads	Equipment	25	$ 11,287	196	17,380
	29	5 Min Showers & Low Flow Shower Heads	Equipment	25	$ 8,545	194	12,062
I (Water Production)	30	Bulk Water Resupply	Resupply	0	$ 25,907	-	-
	31	Tactical Water Purificaiton System (TWPS)	Equipment	1	$ 253,503	204	-
J (Latrine Services)	32	Expiditionary Latrine System (ELS)	Equipment	6	$ 322,789	276	7,925
	33	ELS & Solid Waste Flush Only	TTP	6	$ 322,122	276	6,633
	34	ELS & Pipe Urninals	Equipment	6	$ 319,096	273	5,895
	35	ELS & Waterless Urinals	Equipment	6	$ 323,096	276	7,358
	36	Burn-Out Latrines	Equipment	10	$ 43,284	251	5,916
	37	Chemical Latrines	Equipment	24	$ 22,545	276	7,358
	38	Low Cost TRICON Latrine System (LCTL)	Equipment	3	$ 194,497	307	6,097
K (Waste Water Mngt.)	39	Bulk Waste Water Disposal	Contract	0	$ 364	-	-
	40	Forward Osmosis/Reverse Osmosis Graywater	Equipment	3	$ 760,863	136	-
	41	Black Water Recycler	Equipment	3	$ 552,923	273	-
	42	Deployable Baffled Bioreactor (DBBR)	Equipment	3	$1,063,754	227	-
	43	FORO & DBBR	Equipment	4	$ 413,391	91	-
L (Solid Waste Mngt.)	44	Bulk Solid Waste Disposal	Contract	0	$ 344	-	-
	45	Open Air Burn Pit	Equipment	1	$ 6,208	76	-
	46	Incinerator	Equipment	6	$ 955,614	598	-
	47	Solid Waste Destruction System (SWDS)	Equipment	3	789687.536	64	-

Cost versus performance of infrastructure combinations, 1-, 30-, 183-, and 365-days of operation respectively for CB Bravo.






Millions
Cost ($, USD)
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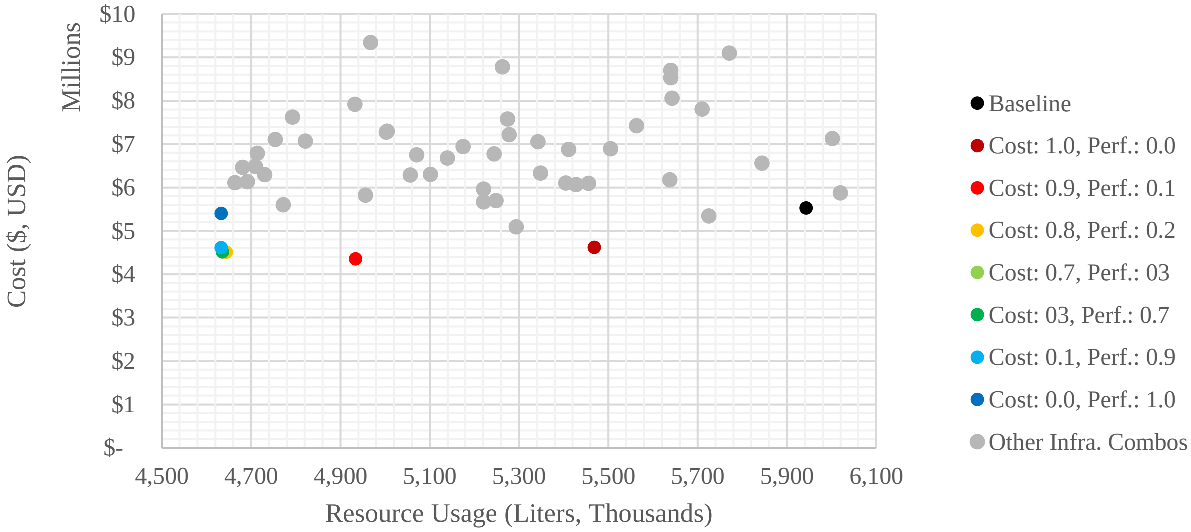
$7
$6
$5
$4
$3
$2
$1
$-
2,300
2,400
2,500
2,600
2,700
2,800
2,900
3,000
3,100
Resource Usage (Liters, Thousands)
Baseline
Cost: 1.0, Perf.: 0.0
Cost: 0.9, Perf.: 0.1
Cost: 0.8, Perf.: 0.2
Cost: 0.7, Perf.: 0.3
Cost: 0.3, Perf.: 0.7
Cost: 0.1, Perf.: 0.9
Cost: 0.0, Perf.: 1.0
Other Infra. Combos


Millions
Cost ($, USD)
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$2
$1
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4,500
4,700
4,900
5,100
5,300
5,500
5,700
5,900
6,100
Resource Usage (Liters, Thousands)
Baseline
Cost: 1.0, Perf.: 0.0
Cost: 0.9, Perf.: 0.1
Cost: 0.8, Perf.: 0.2
Cost: 0.7, Perf.: 03
Cost: 03, Perf.: 0.7
Cost: 0.1, Perf.: 0.9
Cost: 0.0, Perf.: 1.0
Other Infra. Combos

CB Alpha Infrastructure Alternative Database at an operating duration of 365 days

Infrastructure Alternative	Alt. Type	Equip. Count	Alt. Weight (per 100 lb)	Alt. Transpo Cost	Alt. Cost (Unit)	Alt Cost (Units & Trans)	MX Cost	Total Cost	Fuel Usage (liters)	Fuel Trucks Req	FBCF	Potabl Water Usage (liters)	Water Trucks Req	FBCW
AS TEMPER Tent	Equipment	23	207	$ 10,053	$ 18,095	$ 426,238	$ 12,248	$ 499,248	84,016	4	$ 60,762	-	-	$ -
Liner-V1.5	Equipment	23	69	$ 3,843	$ 20,000	$ 463,843	$ 14,289	$ 533,413	76,437	4	$ 55,281	-	-	$ -
Shade-ULCANS	Equipment	23	322	$ 15,228	$ 18,000	$ 429,228	$ 15,922	$ 500,606	76,678	4	$ 55,455	-	-	$ -
Shade-PShade	Equipment	23	414	$ 19,368	$ 24,000	$ 571,368	$ 17,147	$ 645,661	79,017	4	$ 57,147	-	-	$ -
V1.5 Liner & PShade	Equipment	23	483	$ 22,473	$ 44,000	$ 1,034,473	$ 31,435	$ 1,120,933	76,082	4	$ 55,024	-	-	$ -
V1.5 Liner & ULCANS	Equipment	23	391	$ 18,333	$ 38,000	$ 892,333	$ 30,211	$ 975,702	73,502	4	$ 53,158	-	-	$ -
18 PAX per AS TEMPER Tent	TTP	18	162	$ 8,028	$ 18,095	$ 333,738	$ 11,183	$ 402,417	79,500	4	$ 57,496	-	-	$ -
Eliminate Convenience Loads	TTP	23	207	$ 10,053	$ 18,095	$ 426,238	$ 14,289	$ 500,123	82,403	4	$ 59,596	-	-	$ -
60kW Tactical Quiet Generator (TQG)	Equipment	24	853	$ 30,609	$ 25,000	$ 630,609	$ 151,741	$ 1,521,620	1,022,191	54	$ 739,270	-	-	$ -
TM 3-34.46 Layout - 60kW TQGs	TTP	17	605	$ 21,897	$ 25,000	$ 446,897	$ 107,483	$ 1,148,208	821,088	43	$ 593,828	-	-	$ -
Hybrid Power Trailer (HPT)	Equipment	24	528	$ 19,218	$ 95,000	$ 2,299,218	$ 213,000	$ 3,025,876	710,236	38	$ 513,658	-	-	$ -
T-100 (Towable Generator System)	Equipment	24	600	$ 21,738	$ 80,000	$ 1,941,738	$ 187,440	$ 2,774,089	891,719	47	$ 644,910	-	-	$ -
Realistic Grid - 60kW TQGs	Equipment	14	498	$ 23,141	$ 55,000	$ 793,141	$ 88,516	$ 1,317,273	602,327	32	$ 435,616	-	-	$ -
One Large Grid - 60kW TQGs	Equipment	10	356	$ 16,740	$ 85,000	$ 866,740	$ 63,226	$ 1,320,176	539,544	29	$ 390,210	-	-	$ -
Expiditionary TRICON Kitchen System (ETK)	Equipment	2	140	$ 7,038	$ 75,000	$ 157,038	$ 9,940	$ 447,934	70,013	4	$ 50,635	468,886	31	$ 230,321
Fuel-Fired ETK	Equipment	2	154	$ 7,668	$ 85,000	$ 177,668	$ 9,940	$ 469,016	67,863	4	$ 49,080	472,971	31	$ 232,327
Multi Temp. Refrigeration Container System	Equipment	4	536	$ 19,493	$ 40,000	$ 179,493	$ 17,040	$ 206,660	14,003	1	$ 10,127	-	-	$ -
High Efficiency MTRCS	Equipment	4	536	$ 19,493	$ 42,000	$ 187,493	$ 12,425	$ 209,987	13,922	1	$ 10,069	-	-	$ -
High Efficiency MTRCS & Solar Array Shade	Equipment	4	568	$ 20,613	$ 54,000	$ 236,613	$ 14,555	$ 261,217	13,895	1	$ 10,049	-	-	$ -
WH-400 & Modern Burner Unit System (MBU)	Equipment	6	60	$ 3,438	$ 25,000	$ 153,438	$ 5,219	$ 168,784	14,003	1	$ 10,127	-	-	$ -
Solar Water Heater System	Equipment	12	600	$ 21,738	$ 30,000	$ 381,738	$ 11,715	$ 403,503	13,895	1	$ 10,049	-	-	$ -
No metering/Monitoring	N/A	6	0	$ -	$ -	$ -	$ -	$ 16,203	22,404	1	$ 16,203	-	-	$ -
Nonintrusive Load Monitoring (NILM) & Deployable	Equipment	6	12	$ 1,278	$ 2,000	$ 13,278	$ 1,427	$ 25,093	14,363	1	$ 10,387	-	-	$ -
20-lb commercial washers	Equipment	8	16	$ 738	$ 800	$ 7,138	$ 426	$ 546,039	28,005	1	$ 20,254	1,054,993	70	$ 518,221
1/2 Laundry Usage per week	TTP	8	16	$ 738	$ 800	$ 7,138	$ 426	$ 523,645	27,844	1	$ 20,137	1,009,639	67	$ 495,943
10 Min Showers	TTP	0	0	$ -	$ -	$ -	$ -	$ 60,853	70,013	4	$ 50,635	20,803	1	$ 10,218
5 Min Showers	TTP	0	0	$ -	$ -	$ -	$ -	$ 57,707	69,274	4	$ 50,100	15,485	1	$ 7,606
Low Flow Shower Heads	Equipment	25	1	$ 761	$ 40	$ 1,761	$ 44	$ 60,589	69,476	4	$ 50,246	17,380	1	$ 8,537
5 Min Showers & Low Flow Shower Heads	Equipment	25	1	$ 761	$ 40	$ 1,761	$ 44	$ 57,442	68,736	4	$ 49,712	12,062	1	$ 5,925
Bulk Water Resupply	Resupply	0	0	$ -	$ 3	$ 25,907	$ -	$ 9,197,095	-	-	$ -	-	-	$ -
Tactical Water Purificaiton System (TWPS)	Equipment	1	80	$ 4,338	$ 248,500	$ 252,838	$ 36,210	$ 341,530	72,566	4	$ 52,482	-	-	$ -
Expiditionary Latrine System (ELS)	Equipment	6	385	$ 18,072	$ 50,000	$ 318,072	$ 3,728	$ 1,774,613	98,018	5	$ 70,889	2,813,315	186	$ 1,381,924
ELS & Solid Waste Flush Only	TTP	6	385	$ 18,072	$ 50,000	$ 318,072	$ 3,728	$ 1,549,199	97,830	5	$ 70,753	2,354,696	156	$ 1,156,646
ELS & Pipe Urninals	Equipment	6	60	$ 3,438	$ 52,000	$ 315,438	$ 533	$ 1,414,050	96,889	5	$ 70,073	2,092,812	138	$ 1,028,007
ELS & Waterless Urinals	Equipment	6	385	$ 18,072	$ 50,100	$ 318,672	$ 3,728	$ 1,676,289	97,924	5	$ 70,821	2,612,065	173	$ 1,283,068
Burn-Out Latrines	Equipment	10	642	$ 29,628	$ 1,000	$ 39,628	$ 1,775	$ 1,137,548	89,176	5	$ 64,494	2,100,230	139	$ 1,031,651
Chemical Latrines	Equipment	24	120	$ 6,138	$ 498	$ 18,090	$ 14,910	$ 1,386,889	97,924	5	$ 70,821	2,612,065	173	$ 1,283,068
Low Cost TRICON Latrine System (LCTL)	Equipment	3	221	$ 10,706	$ 60,000	$ 190,706	$ 2,130	$ 1,334,793	108,930	6	$ 78,781	2,164,411	143	$ 1,063,177
Bulk Waste Water Disposal	Contract	0	0	$ -	$ 64	$ -	$ -	$ 23,008	-	-	$ -	-	-	$ -
Forward Osmosis/Reverse Osmosis Graywater	Equipment	3	213	$ 10,337	$ 250,000	$ 760,337	$ 5,176	$ 800,501	48,378	3	$ 34,988	-	-	$ -
Black Water Recycler	Equipment	3	257	$ 12,294	$ 180,000	$ 552,294	$ 5,591	$ 627,861	96,755	5	$ 69,975	-	-	$ -
Deployable Baffled Bioreactor (DBBR)	Equipment	3	276	$ 13,158	$ 350,000	$ 1,063,158	$ 5,804	$ 1,127,276	80,629	4	$ 58,313	-	-	$ -
FORO & DBBR	Equipment	4	270	$ 12,888	$ 100,000	$ 412,888	$ 8,733	$ 444,947	32,252	2	$ 23,325	-	-	$ -
Bulk Solid Waste Disposal	Contract	0	0	$ -	$ 44	$ -	$ -	$ 15,990	-	-	$ -	-	-	$ -
Open Air Burn Pit	Equipment	1	0	$ -	$ 5,000	$ 5,000	$ 1,065	$ 25,503	26,876	1	$ 19,438	-	-	$ -
Incinerator	Equipment	6	1200	$ 36,738	$ 150,000	$ 936,738	$ 6,923	$ 1,097,218	212,324	11	$ 153,557	-	-	$ -
Solid Waste Destruction System (SWDS)	Equipment	3	855	$ 30,663	$ 250,000	$ 780,663	$ 5,645	$ 802,830	22,845	1	$ 16,522	-	-	$ -

CB Bravo Infrastructure Alternative Database at an operating duration of 365 days

Infrastructure Alternative	Alt. Type	Equip. Count	Alt. Weight (per 100 lb)	Alt. Transpo Cost	Alt. Cost (Unit)	Alt Cost (Units & Trans)	MX Cost	Total Cost	Fuel Usage (liters)	Fuel Trucks Req	FBCF	Potabl Water Usage (liters)	Water Trucks Req	FBCW
AS TEMPER Tent	Equipment	23	207	$ 10,053	$ 10,464	$ 426,649	$ 12,248	$ 501,479	84,016	4	$ 62,583	-	-	$ -
Liner-V1.5	Equipment	23	69	$ 3,843	$ 4,254	$ 464,254	$ 14,289	$ 535,480	76,437	4	$ 56,937	-	-	$ -
Shade-ULCANS	Equipment	23	322	$ 15,228	$ 15,639	$ 429,639	$ 15,922	$ 502,678	76,678	4	$ 57,117	-	-	$ -
Shade-PShade	Equipment	23	414	$ 19,368	$ 19,779	$ 571,779	$ 17,147	$ 647,784	79,017	4	$ 58,859	-	-	$ -
V1.5 Liner & PShade	Equipment	23	483	$ 22,473	$ 22,884	$ 1,034,884	$ 31,435	$ 1,122,992	76,082	4	$ 56,673	-	-	$ -
V1.5 Liner & ULCANS	Equipment	23	391	$ 18,333	$ 18,744	$ 892,744	$ 30,211	$ 978,522	74,598	4	$ 55,568	-	-	$ -
18 PAX per AS TEMPER Tent	TTP	18	162	$ 8,028	$ 8,439	$ 334,149	$ 11,183	$ 404,551	79,500	4	$ 59,220	-	-	$ -
Eliminate Convenience Loads	TTP	23	207	$ 10,053	$ 10,464	$ 426,649	$ 14,289	$ 502,319	82,403	4	$ 61,382	-	-	$ -
60kW Tactical Quiet Generator (TQG)	Equipment	24	853	$ 30,609	$ 39,554	$ 639,554	$ 151,741	$ 1,552,721	1,022,191	54	$ 761,427	-	-	$ -
TM 3-34.46 Layout - 60kW TQGs	TTP	17	605	$ 21,897	$ 28,352	$ 453,352	$ 107,483	$ 1,172,461	821,088	43	$ 611,626	-	-	$ -
Hybrid Power Trailer (HPT)	Equipment	24	528	$ 19,218	$ 24,909	$ 2,304,909	$ 213,000	$ 3,046,961	710,236	38	$ 529,053	-	-	$ -
T-100 (Towable Generator System)	Equipment	24	600	$ 21,738	$ 28,149	$ 1,948,149	$ 187,440	$ 2,799,827	891,719	47	$ 664,239	-	-	$ -
Realistic Grid - 60kW TQGs	Equipment	14	498	$ 23,141	$ 23,552	$ 793,552	$ 88,516	$ 1,330,739	602,327	32	$ 448,672	-	-	$ -
One Large Grid - 60kW TQGs	Equipment	10	356	$ 16,740	$ 17,151	$ 867,151	$ 63,226	$ 1,332,281	539,544	29	$ 401,905	-	-	$ -
Expiditionary TRICON Kitchen System (ETK)	Equipment	2	140	$ 7,038	$ 7,449	$ 157,449	$ 9,940	$ 461,521	70,013	4	$ 52,153	468,886	31	$ 241,980
Fuel-Fired ETK	Equipment	2	154	$ 7,668	$ 8,079	$ 178,079	$ 9,940	$ 482,657	67,863	4	$ 50,551	472,971	31	$ 244,088
Multi Temp. Refrigeration Container System	Equipment	4	536	$ 19,493	$ 25,262	$ 185,262	$ 17,040	$ 212,732	14,003	1	$ 10,431	-	-	$ -
High Efficiency MTRCS	Equipment	4	536	$ 19,493	$ 25,262	$ 193,262	$ 12,425	$ 216,057	13,922	1	$ 10,370	-	-	$ -
High Efficiency MTRCS & Solar Array Shade	Equipment	4	568	$ 20,613	$ 26,702	$ 242,702	$ 14,555	$ 267,607	13,895	1	$ 10,350	-	-	$ -
WH-400 & Modern Burner Unit System (MBU)	Equipment	6	60	$ 3,438	$ 3,849	$ 153,849	$ 5,219	$ 169,498	14,003	1	$ 10,431	-	-	$ -
Solar Water Heater System	Equipment	12	600	$ 21,738	$ 28,149	$ 388,149	$ 11,715	$ 410,214	13,895	1	$ 10,350	-	-	$ -
No metering/Monitoring	N/A	6	0	$ -	$ 1,149	$ 1,149	$ -	$ 17,838	22,404	1	$ 16,689	-	-	$ -
Nonintrusive Load Monitoring (NILM) & Deployable	Equipment	6	12	$ 1,278	$ 1,689	$ 13,689	$ 1,427	$ 25,815	14,363	1	$ 10,699	-	-	$ -
20-lb commercial washers	Equipment	8	16	$ 738	$ 1,887	$ 8,287	$ 426	$ 574,028	28,005	1	$ 20,861	1,054,993	70	$ 544,454
1/2 Laundry Usage per week	TTP	8	16	$ 738	$ 1,887	$ 8,287	$ 426	$ 550,502	27,844	1	$ 20,741	1,009,639	67	$ 521,048
10 Min Showers	TTP	0	0	$ -	$ 1,149	$ 1,149	$ -	$ 64,037	70,013	4	$ 52,153	20,803	1	$ 10,736
5 Min Showers	TTP	0	0	$ -	$ 1,149	$ 1,149	$ -	$ 60,742	69,274	4	$ 51,602	15,485	1	$ 7,991
Low Flow Shower Heads	Equipment	25	1	$ 761	$ 1,171	$ 2,171	$ 44	$ 62,937	69,476	4	$ 51,752	17,380	1	$ 8,970
5 Min Showers & Low Flow Shower Heads	Equipment	25	1	$ 761	$ 1,171	$ 2,171	$ 44	$ 60,495	69,879	4	$ 52,052	12,066	1	$ 6,227
Bulk Water Resupply	Resupply	0	0	$ -	$ 1,149	$ 25,907	$ -	$ 9,197,095	-	-	$ -	-	-	$ -
Tactical Water Purificaiton System (TWPS)	Equipment	1	80	$ 4,338	$ 4,749	$ 253,249	$ 36,210	$ 343,513	72,566	4	$ 54,054	-	-	$ -
Expiditionary Latrine System (ELS)	Equipment	6	385	$ 18,072	$ 18,483	$ 318,483	$ 3,728	$ 1,847,101	98,018	5	$ 73,014	2,813,315	186	$ 1,451,878
ELS & Solid Waste Flush Only	TTP	6	385	$ 18,072	$ 18,483	$ 318,483	$ 3,728	$ 1,610,280	97,830	5	$ 72,873	2,354,696	156	$ 1,215,196
ELS & Pipe Urninals	Equipment	6	60	$ 3,438	$ 3,849	$ 315,849	$ 533	$ 1,468,599	96,889	5	$ 72,173	2,092,812	138	$ 1,080,045
ELS & Waterless Urinals	Equipment	6	385	$ 18,072	$ 18,483	$ 319,083	$ 3,728	$ 1,743,771	97,924	5	$ 72,943	2,612,065	173	$ 1,348,017
Burn-Out Latrines	Equipment	10	642	$ 29,628	$ 30,039	$ 40,039	$ 1,775	$ 1,192,114	89,176	5	$ 66,427	2,100,230	139	$ 1,083,873
Chemical Latrines	Equipment	24	120	$ 6,138	$ 6,549	$ 18,501	$ 14,910	$ 1,454,372	97,924	5	$ 72,943	2,612,065	173	$ 1,348,017
Low Cost TRICON Latrine System (LCTL)	Equipment	3	221	$ 10,706	$ 11,116	$ 191,116	$ 2,130	$ 1,391,383	108,930	6	$ 81,142	2,164,411	143	$ 1,116,995
Bulk Waste Water Disposal	Contract	0	0	$ -	$ 1,149	$ 1,149	$ -	$ 23,008	-	-	$ -	-	-	$ -
Forward Osmosis/Reverse Osmosis Graywater	Equipment	3	213	$ 10,337	$ 10,747	$ 760,747	$ 5,176	$ 801,959	48,378	3	$ 36,036	-	-	$ -
Black Water Recycler	Equipment	3	257	$ 12,294	$ 12,705	$ 552,705	$ 5,591	$ 630,369	96,755	5	$ 72,073	-	-	$ -
Deployable Baffled Bioreactor (DBBR)	Equipment	3	276	$ 13,158	$ 13,569	$ 1,063,569	$ 5,804	$ 1,129,433	80,629	4	$ 60,060	-	-	$ -
FORO & DBBR	Equipment	4	270	$ 12,888	$ 13,299	$ 413,299	$ 8,733	$ 446,056	32,252	2	$ 24,024	-	-	$ -
Bulk Solid Waste Disposal	Contract	0	0	$ -	$ 1,149	$ 1,149	$ -	$ 15,990	-	-	$ -	-	-	$ -
Open Air Burn Pit	Equipment	1	0	$ -	$ 1,149	$ 6,149	$ 1,065	$ 27,234	26,876	1	$ 20,020	-	-	$ -
Incinerator	Equipment	6	1200	$ 36,738	$ 55,149	$ 955,149	6922.5	1120230.417	212,324	11	$ 158,159	-	-	$ -
Solid Waste Destruction System (SWDS)	Equipment	3	855	$ 30,663	39623.7	789623.7	5644.5	812285.3309	22,845	1	$ 17,017	-	-	$ -

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 074-0188*

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1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From – To)*
25-03-2021	Master's Thesis	September 2019 – March 2021

TITLE AND SUBTITLE

Optimizing Cost And Performance Of Infrastructure Alternatives At Contingency Bases In A Hub-And-Spoke Network

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Rodriguez, Kyle J., Captain, USAF

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(S)
Graduate School of Engineering and Management (AFIT/EN)
2950 Hobson Way
Wright-Patterson AFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT-ENY-MS-21-M-263

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Intentionally left blank

10. SPONSOR/MONITOR'S ACRONYM(S)

AFRL/RHIQ (example)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRUBTION STATEMENT A. APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES
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14. ABSTRACT

Military contingency bases require substantial resources and funding sustain and are often not connected to an infrastructure grid. Infrastructure assets produce the required outputs for sustainment, but are often expensive and inefficient, producing a significant logistical burden. With the increasing near-peer threats of opposing military forces, there is a need for more self-sufficient contingency bases with alternatives that reduce resources usage and the cost of sustainment. Accordingly, the goal of this research is to develop an optimization model capable of selecting infrastructure alternative combinations that minimize the overall resource usage and cost of sustainment at the contingency base level.

15. SUBJECT TERMS
Infrastructure, sustainability, optimization, resource usage, cost

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Steven J. Schuldt, Lt Col, AFIT/ENV
					19b. TELEPHONE NUMBER *(Include area code)*
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Prescribed by ANSI Std. Z39-18