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Optimizing the Environmental and Economic Sustainability of Contingency Base Infrastructure

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OPTIMIZING THE ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY OF CONTINGENCY BASE INFRASTRUCTURE

THESIS

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Abstract

Contingency bases are often located in remote and hostile areas, with limited or no access to established infrastructure grids. This isolation leads to the implementation of standalone systems, comprised of inefficient, resource-dependent infrastructure, which yields a significant logistical burden, creates negative environmental impacts, and increases costs. For example, one forward operating base (FOB) required 22 trucks per day to deliver necessary fuel and water and remove generated wastes. Contingency base planners can mitigate these negative impacts by selecting more efficient and sustainable technologies to support the key infrastructure categories of power production, water production, wastewater management, and solid waste management. However, these alternatives often come at a higher procurement cost and mobilization requirement, which yields additional costs and transportation emissions. Accordingly, planners need to optimal combinations of infrastructure that minimize environmental impacts and life-cycle costs.

The 2018 National Defense Strategy identified near-peer adversaries and an increasingly complex environment defined by rapid technological change as an emerging threat. As DoD missions and capabilities shift to meet this threat, there is a pressing need to design and construct future contingency bases that are agile, resilient, and self-sustaining, while minimizing dangerous resupply convoys. Accordingly, the primary goal of this research effort is to develop novel models for optimizing the design of contingency base infrastructure that provide the capability of minimizing negative

environmental impacts and costs. To accomplish this goal, the research objectives of this study are as follows: (1) conduct a comprehensive review of the current body of literature surrounding infrastructure sustainability practices and logistical impacts associated with contingency base infrastructure; (2) identify and quantify the tradeoffs between environmental and economic sustainability objectives for contingency base infrastructure alternatives; and (3) develop and implement a novel infrastructure sustainability assessment model capable of optimizing the tradeoffs between environmental and economic performance of infrastructure alternatives.

The performance of the developed models was analyzed through case studies of hypothetical FOBs. The case study results demonstrate the novel capabilities of the models in enabling planners to compare infrastructure alternatives and identify optimal combinations of technologies, based on the characteristics of the base and the availability of resources. These capabilities will enable planners to design and construct sustainable contingency bases, creating sites that are more self-sufficient, more economical, and produce fewer environmental impacts.

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First and foremost, I would like to thank my husband for his constant love and support, especially over the past 18 months. I could never articulate how much I appreciate your calming presence and endless patience. Thank you for listening to me talk about greenhouse gasses and gallons of fuel for hours. Next, I must thank my academic advisor, Major Steve Schuldt, for making this thesis possible. Thank you for this research topic, your constant encouragement, and the hours upon hours you spent reviewing and editing my work. My AFIT performance would have been significantly diminished if you hadn't taken me under your wing. To my committee members, thank you for your insight and your time. Each of you played a critical role in making this thesis the product that it was. Additionally, I absolutely must thank my classmates and gym pals. You all kept me sane and reminded me that there is, in fact, life after graduate school. And finally, I would like to thank my parents. Everything I am begins with you.

Jamie E. Filer

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OPTIMIZING THE ENVIRONMENTAL AND ECONOMIC SUSTAINABILITY OF CONTINGENCY BASE INFRASTRUCTURE

I. Introduction

Background

The United States military operates over 800 bases across 80 countries, which enables forces to initiate operations and project strategic power overseas (GAO 2009; Slater 2018). Many of these are contingency bases and are primarily located in remote and hostile areas, detached from established infrastructure grids. These characteristics create a number of sustainability challenges, such as resource-dependence and a constant resupply demand. In one instance, a 600-person forward operating base (FOB) required 22 trucks per day to deliver necessary fuel and water and remove generated wastes (Noblis 2010). These challenges produce negative environmental impacts and increase operational costs. Accordingly, contingency base planners face the challenging task of constructing sites that minimize sustainability challenges and resupply requirements.

To combat these sustainability challenges, the DoD has adopted numerous initiatives to review contingency base design and construction practices and identify opportunities for improvement. For example, the Strategic Environmental Research and Development Program (Noblis 2010) surveyed sustainability challenges within force protection, food, water, wastewater, fuel, power, and solid waste infrastructure. The report noted that by reducing the amount of necessary support material and navigating complex tradeoffs, FOBs can realize direct impacts on logistics costs, convoy casualties, and force effectiveness. The effort concluded by recommending the DoD develop a decision support tool capable of incorporating sustainability best practices.

More recently, the U.S. Army established a program to identify specific technologies capable of “enabling sustainment independence at contingency bases by reducing resupply and backhaul demand” (Gildea et al. 2017a). The program’s goals were to reduce fuel resupply by 25%, water resupply by 25%, waste generation by 50%, and maintain soldier quality of life in order to reach the Army’s vision of a net-zero camp. Accordingly, the program simulated numerous material and non-material solutions capable of sustaining a 50-, 300-, or 1,000-person camp in desert, temperate, or tropical environments. The resulting documentation provides potential fuel, water, and waste (FWW) savings information for more than 30 infrastructure technologies and 20 procedural alternatives.

The civilian construction industry is similarly motivated to mitigate sustainability concerns, applying numerous optimization techniques to the problem. In the civilian industry, researchers primarily focus on minimizing cost and construction time or optimizing the three tenets of sustainability: environmental, economic, and social performance (Fiksel et al. 2012). However, there is limited research evaluating sustainable military infrastructure alternatives in a contingency environment. Consequently, this thesis presents an optimization model that is capable of assisting planners in the challenging task of selecting sustainable infrastructure alternatives that minimize negative environmental and economic impacts.

Problem Statement

Contingency bases are largely sustained by inefficient, resource-dependent infrastructure, which is costly to deploy and maintain throughout its life cycle and produces negative environmental impacts. As the U.S. military continues to leverage contingency bases as strategic platforms in new and dynamic environments, there is a pressing need to design and construct bases that simultaneously minimize environmental impacts, costs, and resupply requirements. Therefore, the purpose of this research effort is to quantify the impact that contingency base infrastructure has on environmental and economic sustainability objectives and optimize tradeoffs among infrastructure alternatives

Research Objectives

The research objectives of this thesis are as follows:

1. Conduct a comprehensive review of the current body of literature surrounding infrastructure sustainability practices and logistical impacts associated with contingency base infrastructure.
2. Identify and quantify the tradeoffs between environmental and economic sustainability objectives for contingency base infrastructure alternatives.
3. Develop and implement a novel, contingency base assessment model capable of optimizing the tradeoffs between environmental and economic performance of infrastructure alternatives.

The Way Ahead

In order to accomplish the aforementioned research objectives, this thesis will follow a scholarly format in which Chapters 3 and 4 are developed as standalone, academic publications. Chapter 2 addresses research objective #1 and provides a comprehensive review of the current literature surrounding environmental and economic sustainability practices, as well as the impact infrastructure has on logistical requirements.

Chapter 3, "Quantifying the environmental and economic performance of remote communities" achieves research objective #2, providing a methodology for quantifying the sustainability of remote community infrastructure. Through the literature, four infrastructure types are identified as critical to a remote site's operational capability: power production, potable water production, solid waste management, and wastewater management. Objective functions capable of calculating the environmental and economic impact of a site's infrastructure are presented. The paper further identifies the resource inputs and outputs for a single remote community in accordance with its manning and duration. Finally, the model is applied to a theoretical, 500-person forward operating base in Southwest Asia to demonstrate its ability to assess infrastructure alternatives. Over the course of three distinct site durations, tradeoffs among objectives are discussed. This paper was presented at the 7th International Conference on Sustainable Development in September 2019 and published in the European Journal of Sustainable Development in October 2019.

Chapter 4, "Optimizing environmental and economic performance of infrastructure at remote communities" presents the development of a novel remote community assessment model capable of computing optimal tradeoffs between environmental and economic performance of infrastructure alternatives. This paper accomplishes research objective #3. Expanding on the objective functions presented in Chapter 3, this paper presents the development of time-dependent functions capable of quantifying a community's environmental and economic performance at increasing site durations. By comparing each alternative to an infrastructure baseline, the model identifies optimal alternatives. Finally, the model is applied to a 300-person military site in an arid region in order to validate its unique capability. The target publication for this manuscript is MDPI's Sustainability Journal, an international, peer-reviewed publication with an impact factor of 2.592.

Finally, Chapter 5 presents the conclusions, research contributions, and recommended future research of the present study.

II. Literature Review

Chapter Overview

The purpose of this chapter is to summarize the current body of literature connecting the topic of sustainable infrastructure design and operation to contingency base planning. First, this chapter begins with a discussion of the literature quantifying the sustainability performance of infrastructure. This section is presented in three distinct sections, each expanding upon the last: (1) environmental sustainability of infrastructure; (2) environmental and economic sustainability of infrastructure; and (3) environmental and economic sustainability of contingency base infrastructure. Second, the logistical impact of contingency sites is discussed. Finally, the chapter ends with a summary of current literature limitations and research opportunities. Figure 1 depicts the areas of existing literature and the resulting research gap that this thesis aims to address.

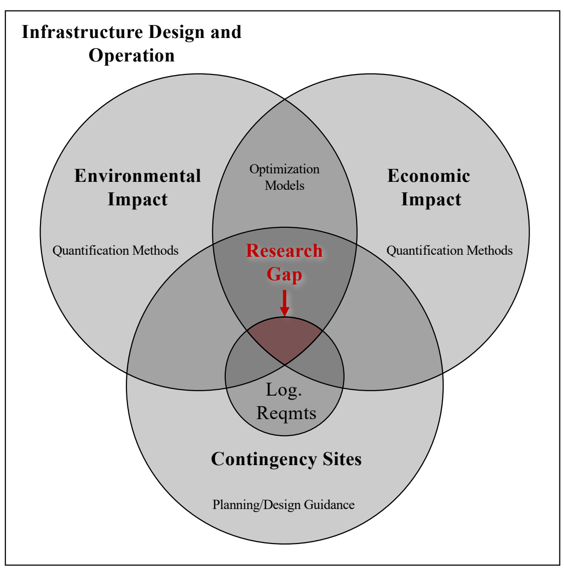

Figure 1. Existing literature and research gap.

Environmental Sustainability of Infrastructure

Environmental sustainability may be measured through various indicators, such as greenhouse gas (GHG) emissions, pollution emissions, energy consumption, embodied emissions, and global warming potential (Kamali and Hewage 2015; Ozcan-Deniz and Zhu 2013). These indicators can be quantified at a static point in time, such as embedded emissions, as impacts due to demolition waste, or over the infrastructure's lifetime via a life cycle assessment (LCA). During operation, approximately 80-90% of the energy use and GHG emissions occur during the operational stage for interior heating, cooling, ventilation, lighting, and appliances, while 10-20% of GHG emissions occur during the material manufacturing, construction, and demolition phase (Cheng et al. 2008). Due to these disparities, the majority of planners prefer an LCA approach.

LCA is a state-of-the-art tool used to evaluate the burdens that a material or method imposes on its surroundings throughout its entire life cycle (Buyle et al. 2013; Marjaba and Chidiac 2016). Because all factors affecting the natural environment, human health, and resource use can be simultaneously considered, LCA avoids problem-shifting between different life cycle stages and influences. Additionally, planners can obtain a comprehensive picture of the long-term effects of their designs.

Buyle et al. (2013) describe the LCA framework's standardized steps, visualized in Figure 2, according to ISO 14044: (1) goal and scope; (2) life cycle inventory (LCI); (3) life cycle impact assessment (LCIA); and (4) interpretation (2006). Goal and scope preclude any evaluation of environmental impacts. This step clarifies the purpose of the LCA and defines the functional units and research boundary. A benefit of LCA is its ability to evaluate materials and methods based on their function rather than their physical properties. Next, the LCI step involves collecting, describing, and validating the performance of the asset in terms of the functional units selected in Step 1. Step 3, LCIA, comprises three required actions. First, one must select impact categories, based on the project goals, that will ultimately be maximized or minimized. Second, the inventory data from Step 2 is assigned to one of these impact categories. Third, the data is computed to determine a category indicator, which characterizes the asset's performance in that specific category. The LCIA step also includes two optional actions: normalization and weighting. Normalizing the data can facilitate simpler computations and allow the model to be applied to a wider range of scenarios, while weighting can account for goals, stakeholder priorities, or regulations. Finally, Step 4 involves the interpretation of results and communication to decision-makers. Due to the vast amount of literature in this research area, the following paragraphs describe various indicators and approaches to evaluating environmental sustainability.

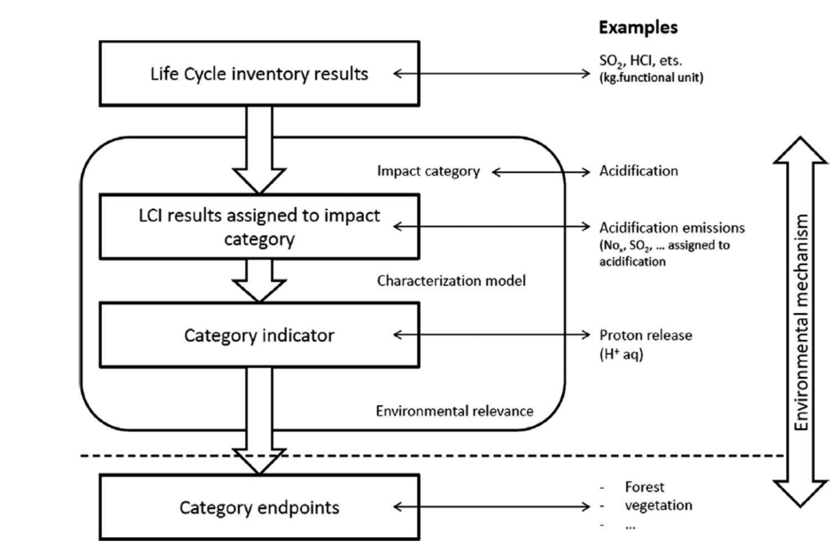

Figure 2. Schematic of life cycle assessment process (Buyle et al. 2013; ISO 14044 2006)

According to the Intergovernmental Panel on Climate Change, the building industry contributes over 18% of all GHG emissions worldwide (IPCC 2014), prompting numerous research efforts aimed at identifying contributing factors and developing emissions minimization tactics. Xing et al. (2008) conducted an LCA of steel and concrete buildings, calculating each building's energy consumption (kJ), embedded GHG emissions (CO_2, CH_4, and CFC), and principal pollution emissions (O_3, CO, NO_x, PM_{10} and SO_x) on a per-square-foot basis. Pollution emissions were further divided to distinguish between overall emissions and urban or regional emissions. The results showed that over a 50-year life cycle, concrete building materials consume 24.9% more energy and produce 39.1% more CO_2 than steel. However, this effort also found that due to lesser thermal properties, steel buildings consume 18.4% more energy than concrete buildings during the operational stage for heating and cooling purposes. Therefore, while steel buildings emit 1% fewer emissions over their life cycle than concrete, they consume 7.9% more energy. These results show that while the embedded emissions of construction materials do affect life-cycle emissions, the building's operational requirements may be considerably more impactful overall.

Where Xing et al. compared construction materials, Mao et al. (2013) compared construction methods. In order to contrast the environmental impact of conventional construction with off-site prefabrication, the authors quantified GHG emissions from the following five sources: embodied emissions of materials, transportation of materials, transportation of construction waste and soil, transportation of prefabricated items, operation of equipment, and construction techniques. Global warming potential (GWP) was used to convert the most prominent GHGs – that is, CO_2, CH_4, and N_2O – into CO_2

equivalents (CO_2e). The research effort found that prefabrication produces fewer emissions than conventional methods at 336 kg CO_2e/m^2 versus 368 kg CO_2e/m^2. This effort also concluded that, of the four factors with the potential to reduce emissions, embodied emissions of materials and transportation of materials may make the most significant impacts, at up to 86.5% and 18.3% reduction, respectively.

According to the Intergovernmental Panel on Climate Change (IPCC), nearly two-thirds of a building's emissions stem from electricity and heat production (2014). Therefore, other research efforts have analyzed power production infrastructure specifically. For example, the World Nuclear Association produced a research compilation of 83 publications which quantified life-cycle GHG emissions from various electricity production methods, as summarized in Figure 3. Of note, oil, the most common source of electrical power for contingency bases, emits 1.5, 8.6, and 26 times more emissions than natural gas, solar photovoltaic, and wind generation methods, respectively.

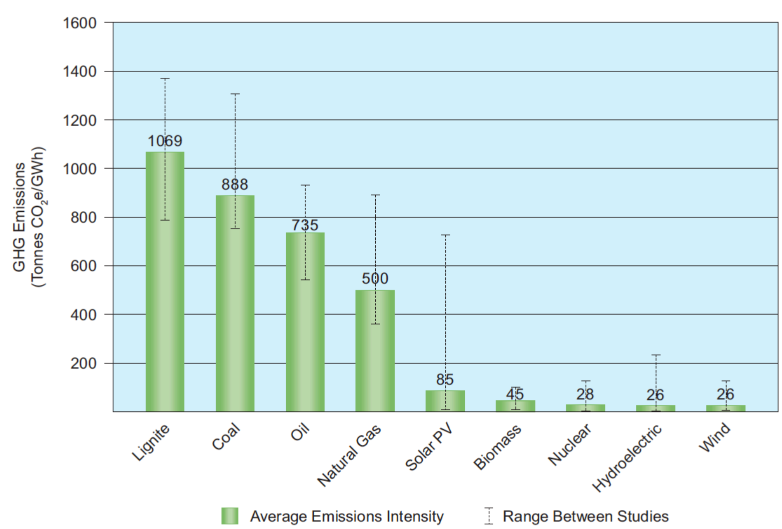

Figure 3. Summary of life-cycle GHG emission intensities (WNA 2011).

To quantify the potential impact of minimizing electricity production, Siler-Evans et al. (2012) developed marginal emissions factors for coal, gas, and oil-fired generation plants in the U.S. The authors determined that the benefits of mitigating one megawatt-hour of electricity are greatly impacted by geographical region. For example, eliminating one megawatt-hour of electricity in the Midwest may avert 70% more CO_2, 12 times more SO_2, and 3 times more NO_x emissions than it would in the West due to production methods and local regulations.

Potable water production and distribution is another area of concern for buildings. By 2025, over a quarter of the world's population will face water scarcity (WWAP 2003). Additionally, fossil fuel depletion and related climate change consequences are leading to shifts in energy usage for water purification purposes. Accordingly, Racoviceanu et al. (2007) and Vince et al. (2008) developed impact assessment tools to evaluate potable water production methods, introducing environmental criteria into the planning process. Racoviceanu's model estimated the total energy usage and the resulting GHG emissions from the City of Toronto's municipal water treatment system. Vince's model broadly evaluated life-cycle performance by considering impacts on climate change, resource depletion, human health, and ecosystem quality. These impacts were broken down by life-cycle phase for various treatment methods, such as ultrafiltration and reverse osmosis. Though differing in computational methodologies, both research efforts determined that the primary source of environmental impact is the plant's electricity production, not the water production itself. This conclusion underscores the need to introduce sustainable practices into energy production infrastructure due to its impact on all other infrastructure systems.

Waste management systems also contribute to negative environmental impacts. Methane, or CH_4, is considered the most significant GHG emitted from wastewater management (El-Fadel and Massoud 2001). At a GWP 21 times greater than CO_2, El-Fadel and Massoud estimated country-wide methane emissions in Lebanon as opposed to developed and developing countries. While anaerobic processes (i.e., lagoons) are desirable due to possible heat recovery, rising costs of sludge disposal, low energy consumption, and reduced CH_4 emissions, they are less prevalent in developed countries due to limited land availability. However, where open lagoons are utilized, capturing CH_4 for energy production is a commonly recommended measure to mitigate emissions.

Further, various studies have quantified emissions from solid waste management practices. While common, particularly in developing countries and contingency sites, landfilling is considered the most destructive waste management method, with emissions factors ranging from 1.2-1.67 tons CO_2e/ton waste (Barton et al. 2008; Batool and Chuadhry 2009). According to Barton et al., incorporation of gas flaring may decrease emissions to 0.19 tons CO_2e/ton waste, and systems that utilize both gas flaring and energy production can further decrease emissions to 0.09 tons CO_2e/ton waste. Open dumping, another common method at undeveloped sites, has a marginal improvement over traditional landfilling with an emissions factor of 0.74 tons CO_2e/ton waste. Moreover, though generation rates depend upon population size, wealth, and urbanization, supplementary practices, such as source reduction and recycling, can diminish the volume of waste to be disposed of regardless of management selection (Friedrich and Trois 2011). For established military sites, Borglin et al. (2010) recommend adoption of source reduction, recycling, composting, and waste-to-energy systems. However, the authors also concede that waste disposal options are regionally dependent due to variations in climate, population, traffic, noise, and local laws and regulations.

While the aforementioned papers evaluate environmental sustainability challenges and impacts of infrastructure components, they do not consider the economic tradeoffs of incorporating potentially expensive, technologically advanced alternatives.

Environmental and Economic Sustainability of Infrastructure

Further studies optimized tradeoffs between the environmental and economic performance of infrastructure. Coello (2005) defined optimization as the process by which one determines the best solution to a problem based on a set of constraints. When this process includes just one objective, the goal is to determine one ideal solution. A multi-objective optimization problem, however, occurs when two or more objectives must be enhanced simultaneously. Generally, these objectives are in direct conflict with each other, so there is no single, best solution. Rather, the intent of a multi-objective optimization model is to determine a set of nondominated solutions, termed the Pareto front, where each solution optimizes at least one objective while identifying tradeoffs in the other objective categories. From this list, decision-makers can select any number of available solutions that would maximize their primary concerns, leading to improved solutions and a broader knowledge of the entire decision space (Liu et al. 2015).

Ozcan-Deniz et al. (2012; 2013) optimized facility and highway construction decisions to minimize time, cost, and environmental impact in terms of GWP. The authors utilized LCA methods and multi-objective optimization, including genetic algorithms, to identify potential solutions. Other efforts considered the sustainability triple bottom line (TBL), that is, environmental, economic, and social objectives (WCED 1987). Each of these objectives may be measured through the use of indicators. Kamali and Hewage (2015) conducted a comprehensive review of the most prominent sustainability indicators currently used in the literature and industry to assess buildings. The authors presented a refined list of 16 environmental, 9 economic, and 12 social indicators based on their frequency of use within reputable, peer-reviewed sources. Common economic indicators include design and construction, operating, maintenance, and end of life costs.

Karatas and El-Rayes (2014) first quantified the TBL performance of urban neighborhoods and then optimized performance tradeoffs for housing projects (2015). In the latter paper, economic performance was measured by the building's life-cycle cost, with metrics including initial investment costs, operating and maintenance costs, energy and utility costs, capital replacement costs, and residual value. Kamali and Hewage (2017) optimized TBL objectives to compare modular versus conventional construction methods. The authors selected sustainability indicators based on survey results of construction professionals, who ranked the applicability and importance of each option. Kua and Lee (2002) took an alternate approach, showcasing the ability of intelligent buildings to contribute to sustainable development in the built environment. The authors recommended that rather than replace current buildings, planners should consider incorporating intelligent technologies into current buildings. These changes can maximize building lifespans and increase efficiencies while minimizing total costs.

Abdallah and El-Rayes (2015) also evaluated the potential of upgrade measures to impact sustainability objectives. By focusing on measures that were feasible without major reconstruction, the authors intended to minimize negative environmental impacts under a set budget and specified operational performance. Minimizing impacts was approached by reducing GHG emissions, refrigerant impacts, mercury-vapor emissions, light pollution, and water consumption. Each metric was designed such that it represented the annual impact and accounted for the change in climate throughout all four seasons. Then, a case study was developed to determine the model's feasibility when applied to an existing rest area building. This facility was selected due to its high traffic volume and high levels of damaging environmental impacts. Upgrade budgets from $10K to $200K were considered, and near-optimal solutions were determined at various costs. Each solution set was able to provide a detailed description of the fixtures and equipment to be upgraded, type of renewable energy system to be installed, and/or a new method of managing the building's solid waste. Decision-makers can use this model to optimize the outcome of limited renovation budgets. While the aforementioned papers do address tradeoffs between the environmental and economic performance of infrastructure, they do not consider remote and isolated communities.

Environmental and Economic Sustainability of Contingency Site Infrastructure

The following sources quantitatively evaluate the environmental and economic performance of contingency base infrastructure. El-Anwar et. al (2010) sought to maximize the sustainability of post-disaster recovery housing efforts. Similar to contingency bases, most post-disaster housing sites were originally designed for shortterm operations at no more than 18 months of use. However, the authors were motivated by the recent realities of Hurricanes Katrina and Rita, which left residents in temporary housing up to 44 months and caused policymakers to search for improved alternatives. To this end, El-Anwar et al. established 36 performance indicators categorized into environmental performance, social welfare, economic, and public welfare indices. Utility theory, a method of accounting for differing units, enabled mathematical operations, and weights were developed to represent decision-maker priorities. Finally, the authors leveraged weighted integer programming to generate a set of optimal configurations from the temporary housing alternatives. While thorough, this effort only addressed post-disaster lodging, which did not account for the unique infrastructure alternatives and challenges faced by contingency military bases.

For example, military contingency bases face the particular challenge of acquiring and transporting oil and its diesel fuel byproduct, which are critical resources. In 2008, over 68 million gallons of fuel per month were required to support military forces in Iraq and Afghanistan (GAO 2009). To lessen this demand, the U.S. Government Accountability Office conducted a study addressing: (1) efforts to reduce fuel demand at forward-deployed locations, and (2) approaches to managing fuel demand at such locations (GAO 2009). The report noted that while aircraft require a substantial volume of fuel, the single largest fuel consumer on the modern battlefield is the generator. These generators primarily power base support infrastructure such as heating, cooling, and lighting. At the time of the study, environmental emissions were of limited concern; instead, the report focused on cost and member safety due to excessive convoy operations. As an example, government officials reported that in June 2008 alone, 44 trucks and 220,000 gallons of fuel were lost due to attacks and other unforeseen events.

To combat such a substantial fuel requirement, various studies have offered methods to limit consumption. Craparo and Sprague (2018) proposed optimal scheduling of tactical power generation equipment, coordinating both supply- and demand-side management. By applying the model to operational data from a 45-person support system, the authors estimated that 28% fuel reduction could be realized while maintaining indoor building temperatures for 97% of the assessed timeframe. Thomsen et al. (2019) also addressed generator fuel consumption by evaluating the prospect of exchanging prime power generators for solar array equipment. The authors determined that the replacement of a single 800 kW generator with an optimized solar array and battery storage could save 1.9 million liters of fuel and 100 fuel tanker trucks per year with less than a 1% drop in reliability. To underscore the potential benefit of avoiding fuel-based power generation, Zhu et al. (2009) conducted in-plume tests to establish particulate matter (PM), carbon monoxide (CO), and nitrogen oxide (NO_x) emissions factors (EF) for 30-, 60- and 100-kW military generators. Table 1 summarizes Zhu's results as compared to Environmental Protection Agency (EPA) estimates.

Table 1. Fleet average emissions factors for tested generators (Zhu et al. 2009).

	No_x (g/kg fuel)	CO (g/kg fuel)	PM (g/kg fuel)
Average	31	17	1.2
Standard Deviation	8.4	7.3	0.6
Coefficient of Variance	27%	42%	51%
EPA Estimate	85	18	6

Further studies evaluated other military-specific challenges, such as solid waste management. In particular, open burning of waste is of critical concern due to its prominent use as an expedient waste mitigation tactic during the recent conflicts in Iraq and Afghanistan (Woodall et al. 2012). In one example, Joint Base Balad, Iraq was reported to have burned nearly 200 tons of waste per day during peak troop surges in 2008 (DoD 2010). Harmful emissions from waste burning include carbon dioxide (CO_2), particulate matter (PM_{10}, $PM_{2.5}$), volatile organic compounds (VOC), polyaromatic hydrocarbons (PAHs), and polychlorinated and polybrominated dioxins/furans (PCDD/F, PBDD/F) (Aurell et al. 2012; Blasch et al. 2016; Woodall et al. 2012). While these studies do consider environmental and economic performance tradeoffs of contingency site infrastructure, they do not account for associated logistical requirement tradeoffs.

Logistical Impact of Contingency Site Infrastructure

The following section describes efforts to quantify and minimize logistical requirements stemming from contingency site infrastructure. Poreddy and Daniels (2012) proposed a base camp model that utilized a systems-engineering approach to define relationships between subsystems. Their focus was on improving forward operating base (FOB) sustainability by estimating the required input and output resources of each asset type. The primary resources evaluated were electricity, fuel, potable water, bottled water, storage area, personnel, gray wastewater, black wastewater, solid waste, food service, geographical footprint, and maintenance hours. To demonstrate the validity of their model, the authors created a hypothetical 600-soldier FOB with 40 essential facilities, where each facility was assessed on the resources it consumed and/or produced. These facility types were categorized into the following: buildings (to include housing, administration, and services); latrines; power production and distribution; water production and distribution; wastewater treatment; airfield; solid waste treatment; security; MWR; medical; fire protection; communications; and transportation networks. Their efforts resulted in the creation of a linear model capable of characterizing the interconnectedness of infrastructure components and their impact on overall resource requirements.

Putnam et al. (2016) also addressed logistical requirements for contingency sites. In particular, the authors proposed a unique method of volumetric accounting to quantify the volume of resources entering and exiting the site each day. Each resource type, such as fuel, water, and waste, was assigned a conversion factor denoting how much of that resource must cross the site's boundary. Sites that are entirely dependent upon local services may be appointed conversion factors of 1. In contrast, a site with its own natural water supply may have a water conversion factor less than 1. These values were then plotted against the infrastructure's initial mobilization requirement, as shown in Figure 4. Mobilization requirements were quantified in Tricon equivalent volumes (TEV) to represent the infrastructure's shipped volume. This plot depicts the results of 256 combinations of design changes and identifies four possible solutions that optimized the selection of infrastructure components with minimal logistical requirements

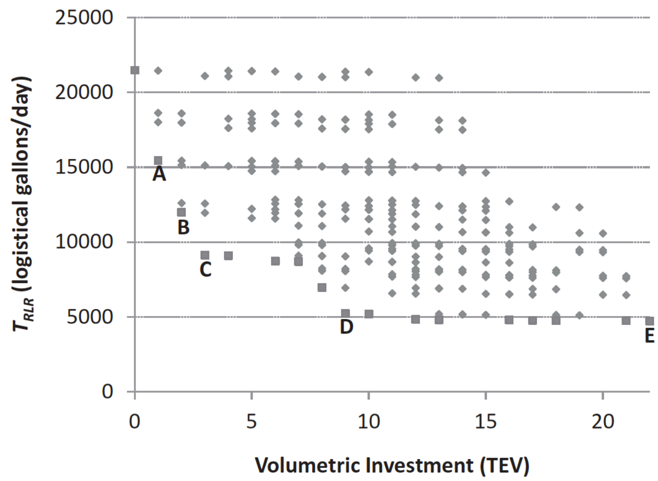

Figure 4. Initial mobilization requirement versus daily logistical requirement for 256 combinations of infrastructure changes (Putnam et al. 2016).

Research Limitations and Areas of Opportunity

Despite the contributions of the aforementioned research efforts, there is no reported research that optimizes the selection of contingency base infrastructure in order to minimize sustainability challenges and resupply requirements. While there have been many efforts to quantify and optimize the environmental and economic impacts of infrastructure, none of these papers considered contingency bases. Similarly, the literature on contingency base sustainability primarily focused on fuel consumption, emissions, or logistical requirements – not all three.

Accordingly, the following research contribution will first identify and quantify tradeoffs between environmental and economic sustainability objectives for remote community infrastructure. Finally, this thesis will present a novel, contingency base assessment model capable of optimizing tradeoffs between the environmental and economic performance of infrastructure alternatives. This model will assist planners in their challenging task of constructing sites with reduced costs, environmental impacts, and resupply requirements.

III. Scholarly Article 1: Quantifying the Environmental and Economic Performance of Remote Communities

Jamie E. Filer and Steven J. Schuldt, Ph.D., P.E.

Abstract

Remote communities such as oil production sites, post-disaster housing camps, and military forward operating bases (FOB) are often detached from established infrastructure grids, requiring a constant resupply of resources. In one instance, a 600-person FOB required 22 trucks per day to deliver necessary fuel and water and remove generated wastes. This logistical burden produces negative environmental impacts and increases operational costs. To minimize these consequences, construction planners can implement sustainability measures such as renewable energy systems, improved waste management practices, and energy-efficient equipment. However, integration of such upgrades can increase construction costs, presenting the need for a tool that identifies tradeoffs among conflicting criteria. To assist planners in these efforts, this paper presents the development of a novel remote site sustainability assessment model capable of quantifying the environmental and economic performance of a set of infrastructure alternatives. Through field data and literature estimates, a hypothetical FOB is designed and evaluated to demonstrate the model's distinctive capability to accurately and efficiently assess construction alternatives. The proposed model will enable construction planners to maximize the sustainability of remote communities, creating sites that are more self-sufficient with reduced environmental impacts.

Introduction

Remote communities such as oil production sites, post-disaster housing camps, and military forward operating bases (FOB) are often detached from established infrastructure grids, requiring a constant resupply of resources. Their inefficient, resource-dependent infrastructure yields a significant logistical burden, which creates negative environmental impacts and increases operational costs. For example, in 2004, a set of 21 remote communities in northern Canada relying on diesel generators required an energy output of 50 gigawatt-hours (Arriaga et al. 2013). Operating these generators cost $40M and emitted 40,000 tons of carbon dioxide (CO_2) – the equivalent annual emissions of nearly 8,000 passenger vehicles. Accordingly, remote community construction planners are presented with the challenging task of evaluating the impacts of their infrastructure alternatives in order to minimize environmental impacts while also minimizing costs.

A number of research studies have been conducted that: (1) evaluate sustainability challenges faced by remote communities; and (2) quantify the environmental impact of infrastructure alternatives. First, several studies were conducted that identified sustainability challenges at remote communities and proposed mitigation efforts. The Strategic Environmental Research and Development Program (SERDP) analyzed the financial, environmental, and safety costs associated with United States (US) military FOB design and operation (Noblis 2010). The report proposed reducing resource consumption, minimizing waste through reuse, and incorporating more energy-efficient technology as areas for future research investment. Another source quantified FOB resupply requirements and evaluated infrastructure alterations to minimize logistical resupply (Putnam et al. 2016). Additionally, Arriaga et al. (2013, 2014) identified more than 280 northern and remote communities in Canada with limited or no access to electrical grids. The authors demonstrated that incorporation of renewable energy measures such as wind and solar systems may reduce fuel consumption and offset high operating costs and CO_2 emissions.

Second, numerous studies have computed the environmental impact of infrastructure alternatives for remote communities, including power production (Arriaga et al. 2013; Craparo and Sprague 2018; WNA 2011), water production (Cave et al. 2011; Vince et al. 2008), solid waste management (Batool and Chuadhry 2009; Cherubini et al. 2009), and wastewater management (El-Fadel and Massoud 2001; Racoviceanu et al. 2007). Further, additional studies have generated combinations of infrastructure alternatives that deliver optimal tradeoffs between environmental performance and cost through multi-objective optimization (Abdallah and El-Rayes 2016; El-Anwar et al. 2010; Karatas and El-Rayes 2016; Ozcan-Deniz et al. 2012).

Despite the contributions of the aforementioned studies, there is no reported research that focused on quantifying tradeoffs between environmental and economic performance of remote community infrastructure alternatives. Accordingly, this paper presents the development of a novel remote site sustainability assessment model capable of quantifying the environmental and economic performance of a set of infrastructure alternatives in order to assist planners in maximizing the sustainability of remote community design.

The following sections of this paper describe: (1) selecting relevant decision variables; (2) formulating objective functions; (3) defining model constraints; (4)

identifying model input data; and (5) evaluating model performance through an application example.

Model Formulation

This section presents the development of a model capable of quantifying the environmental and economic performance of remote community planning and construction. The development of this model includes identifying remote community decision variables and formulating sustainability objective functions.

Decision Variables

The decision variables utilized in the following model are selected to represent the infrastructure types required to support remote community facilities that have the greatest impact on sustainability objectives. The model considers the following types of infrastructure: (1) power production; (2) potable water production; (3) solid waste management; and (4) wastewater management. Within each type of infrastructure, multiple alternatives may be considered, and at least one alternative must be selected. For example, the function of solid waste disposal may be met with either incineration or landfilling. Table 1 in the application example summarizes potential alternatives within each type.

Objective Functions

For each decision variable alternative, the present model quantifies resource inputs and outputs that impact sustainability. For example, each of the aforementioned solid waste disposal alternatives have a requirement-driven input (volume of waste, gallons of fuel, etc.) and an environmental impact output (such as greenhouse gas (GHG) emissions). Each alternative also has an associated cost. While incinerator equipment may have a higher up-front cost than a landfill, its resulting GHG emissions may be less than an untreated landfill for the same volume of waste.

The first objective function is designed to quantify the impact that a remote community's infrastructure has on its surrounding environment. Measured in volume of equivalent carbon dioxide emissions (metric tons CO_2E/day), Equation (1) calculates the environmental impact for each infrastructure alternative as a function of its energy consumption and resource transportation requirements. Equation (2) calculates the environmental impact of a set of alternatives (i.e. remote community site). Emissions due to energy consumption are calculated as a function of daily fuel or power consumption (tons of CO_2/gallon diesel fuel or tons of CO_2/kW). The impact of resource transportation via ground is calculated as a function of vehicle efficiency (km/gal) and distance traveled (km). Resource transportation via air is calculated with Equation (3) a function of aircraft efficiency, distance traveled, and cargo transported. Increasing volumes of CO_2 correspond to increasingly negative impacts on the environment.

$$EI_i = EI_i^{ec} + EI_i^{rt} \tag{1}$$

$$EI_{site} = \sum_{j=1}^{J} EI_{ij} \tag{2}$$

Where EI = environmental impact (tons CO_2E/day);

i = infrastructure alternative;

j = infrastructure type;

J = total infrastructure types;

site = set of one infrastructure alternative for each infrastructure type;

EI^{ec} = environmental impact due to energy consumption (tons CO_2E/day); and

EI^{rt} = environmental impact due to resource transportation (tons CO_2E/day).

$$EI^{rt}(air) \; = EF_{air} * cargo_{air} * distance_{air} \tag{3}$$

Where EI^{rt}(air) = environmental impact of resource transportation via air (tons CO_2);

EF_{air} = emissions factor of aircraft (tons CO_2/ton cargo/km);

$cargo_{air}$ = cargo transported via air (tons); and

$distance_{air}$ = distance traveled via aircraft (km).

The second objective function quantifies the economic performance of a set of remote community infrastructure alternatives. Equation (4) accounts for initial, operating, and maintenance costs of each infrastructure alternative computed in cost per day ($/day). Equation (5) calculates the total cost of a set of infrastructure alternatives. Initial costs are calculated as a function of purchase, delivery, and setup costs per day of site duration. Operating costs are calculated as a function of fuel consumption, contractor costs, manpower, materials, and daily transportation costs. Maintenance costs are a function of manpower and materials required to maintain the asset's working condition.

$$TC_i = \; TC_i^{ic} + \; TC_i^{oc} + \; TC_i^{mc} \tag{4}$$

$$TC_{site} = \sum_{j=1}^{J} (TC_{ij}) \tag{5}$$

Where TC = total cost of all infrastructure alternatives ($/day);

i = infrastructure alternative;

j = infrastructure type;

J = total infrastructure types;

site = set of one infrastructure alternative for each infrastructure type;

TC^{ic} = initial purchase and setup cost ($/day);

TC^{oc} = operating cost ($/day); and

TC^{mc} = maintenance cost ($/day).

Model Constraints

The present model is designed to consider and comply with all remote site characteristics. Resource requirements are dependent upon the population, duration and identified planning factors, which enables the results to be scaled appropriately. Environmental impacts and costs due to resource transportation are dependent upon the site location, available transportation method, and resource weight, which enables the model to apply to various locations. Further, the model is designed such that each alternative may be combined with any other alternative. For example, each potable water production system may be powered by any of the available power generation alternatives.

Model Input Data

Remote community construction planners must identify all remote site characteristics, planning factors, and infrastructure alternative data. Remote site data includes: (1) required personnel (persons); (2) location; (3) duration (days); (4) delivery method (ground, air, or sea); and (5) distance to commercial utilities (km). Planning factor data includes: (1) power requirement (kW/person); (2) potable water requirement (gal/person); (3) solid waste production (kg/person); and (4) wastewater production (gal/person). Infrastructure alternative data includes: (1) feasible alternatives for each infrastructure type (power production, potable water production, wastewater management, and solid waste management); (2) resource production rate (kW/day, gal/day, or kg/day); (3) resource consumption rate (kW/day, gal/day, or kg/day); (4) emissions factors (tons CO_2/kW or tons CO_2/gal); and (5) costs ($/unit, $/gal, or $/man-hour).

In order to effectively evaluate the environmental and economic life-cycle costs of infrastructure, boundaries must be identified and consistently adhered to. The present model was assumed to be bounded such that the environmental impacts and costs associated with the purchase and operation of each infrastructure alternative within the remote community are accounted for. Transportation from the alternative's primary distribution source (such as ground transportation from local town or air transportation from major metropolis or supplier) was also included, as these factors can have significant impacts on an alternative's performance. Production of resources and equipment off-site or by entities other than the remote community were not considered.

Application Example

In order to demonstrate the model's unique capability, a hypothetical military FOB is designed, and multiple infrastructure alternatives and durations are evaluated according to the proposed objective functions. A military base was chosen for the following example due to the availability of resource planning factors and historical data.

This case study was designed to simulate a typical, mid-sized FOB in Southwest Asia. For this example, the required input data includes: (1) remote site characteristics; (2) planning factors; and (3) infrastructure alternative data. First, remote site characteristics include a 500-person remote community in Southwest Asia that must sustain living conditions for 180, 365, or 730 days. Common resources such as potable water may be transported via land from a local city center 24 km to the community. Uncommon resources such as solar panel equipment, military generators, and incinerators may be transported via air from a supplier located in Central Europe, 5,172 km from the community. Second, planning factors were identified for power, potable water, solid waste, and wastewater through historical data and US Army design guides (Noblis 2010). Third, infrastructure alternatives and their consumption rates were identified through various sources, as seen in Table 1. Throughout the case study, energy consumption emissions factors were held constant to ensure consistency in results (US EPA 2018).

Table 2. Sample infrastructure alternative data.

	Data	Value	Units	Source
Site characteristics	Personnel	500		
	Location	Southwest Asia		
	Duration	180/365/730	days	
	Distance for ground transport	65	km	
	Distance for air transport	5172	km	
Planning Factors	Power requirement	1	kW/person/day	(Noblis 2010)
	Potable water requirement	35	gal/person/day	(Noblis 2010)
	Solid waste production	4.53592	kg/person/day	(Noblis 2010)
	Wastewater production	35	gal/person/day	(Noblis 2010)
Alternatives	**Energy Production**			
	Mobile Electric Power Unit (MEP-806)	60	kW/unit	(635 MMG 2017)
	Basic Expeditionary Airfield Resource Power Unit (BPU)	800	kW/unit	(635 MMG 2017)
	Solar Panels	varies		(Noblis 2010)
	Potable Water Production			
	Reverse Osmosis Water Purification Unit (ROWPU)	30,000	gal water/day	(Gibbs 2012a)
	Import water tankers	varies		(Noblis 2010)
	Import bottled water	varies		(Noblis 2010)
	Wastewater Disposal			
	Export off-site	varies		(Noblis 2010)
	Sewage lagoons	varies		(Gibbs 2012b)
	Solid Waste Disposal			
	Incineration	36	gal fuel/ton waste	(Putnam et al. 2016)
	Landfill	varies		(Gibbs 2012c)
	Emissions Factors			
	Electricity	7.07×10^{-4}	ton CO_2/kWh	(US EPA 2018)
	Diesel	1.02×10^{-2}	ton CO_2/gal fuel	(US EPA 2018)
	Aircraft	4.10×10^{-2}	ton CO_2/ton cargo/km	(Chao 2014)

By considering one alternative per each of the four infrastructure types, the developed model was used to generate 36 unique sets of infrastructure alternatives (i.e. sites). For each distinct duration, the model identified the associated EI and TC tradeoffs of each site. Figures 5, 6, and 7, display the set of solutions generated for 180-, 365-, and 730-day durations, respectively. For each duration, a set of notable solutions is highlighted in Table 2. In Figure 5, site S7 represents the solution with the lowest EI

(20.23 tons CO_2/day), while site S34 represents the solution with the highest EI (39.74 tons CO_2/day) for a duration of 180 days. Conversely, site S4 represents the lowest TC ($27,477.31/day) and site S33 represents the highest TC ($115,717.41/day). Durations this short favor infrastructure alternatives with lower up-front environmental impacts and costs. For example, of the three feasible energy production alternatives, the MEP-806 generator produced the lowest EI^{rt}. Therefore, it resulted in the lowest total EI even though it had the highest EI^{ec}.

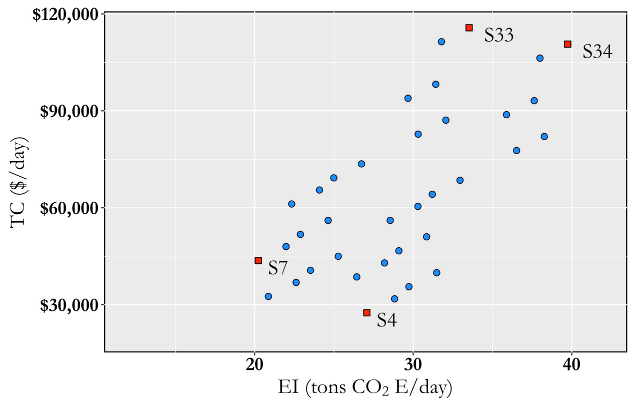

Figure 5. Site solutions for 180-day duration.

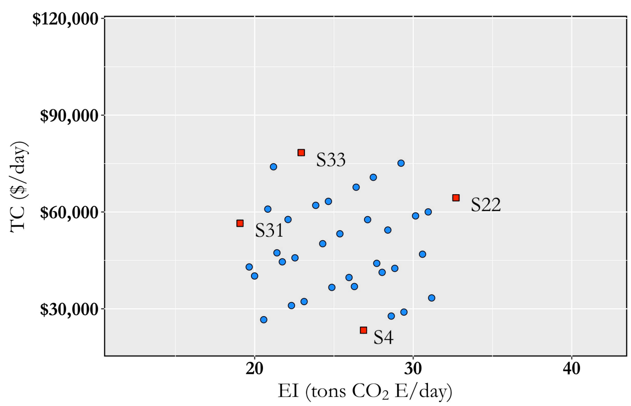

Figure 6. Site solutions for 365-day duration.

With an increased duration of 365 days, Figure 6 shows that the minimum and maximum EI solutions switched to S31 (19.08 tons CO_2/day) and S22 (32.70 tons CO_2/day), respectively, due to varying energy production alternatives. While the solar panel alternative was found to result in the highest EI and highest TC at 180 days, it was found to have the lowest EI and highest TC at 365 days. This is likely due to the solar panels' high initial transportation requirement and low daily energy consumption. Consequently, as site duration increases, alternatives with higher up-front investments may become environmentally feasible if they produce less emissions per day.

Further, when the site's duration was increased to 730 days as seen in Figure 7, the minimum and maximum TC solutions shifted to S28 ($21,201.91/day) and S21 ($64,804.67/day), respectively. At this duration, solar panels were found to result in the lowest EI and lowest TC. Again, the alternative's high initial investment became less apparent over time due to its low operating and maintenance costs. Of note, incineration as a solid waste management alternative was found to have a lower EI and higher TC than landfilling at each duration. Meanwhile, importing bottled water and exporting wastewater off-site were consistently found to result in both the highest EI and highest TC, making them the least sustainable potable water production and wastewater management methods. Moreover, the EI and TC of each solution, on average, dropped 6.05 tons CO_2/day and $20,284.23/day when the duration was extended from 180 to 730 days.

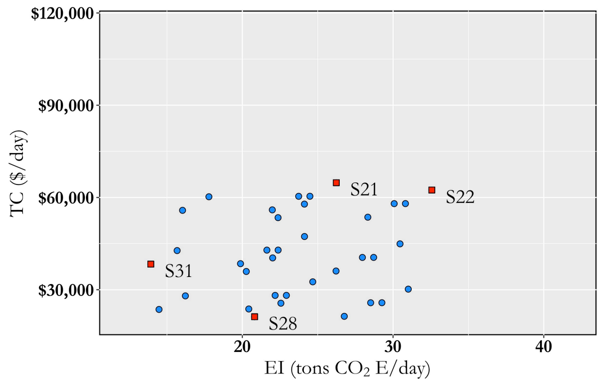

Figure 7. Site solutions for 730-day duration.

Table 3. Summary of notable solutions.

	180-Day Duration			
	S7 (lowest EI)	S34 (highest EI)	S4 (lowest TC)	S33 (highest TC)
Energy Production	MEP-806s	Solar Panels	MEP-806s	Solar Panels
Potable Water Production	Import water tankers	Import bottled water	ROWPUs	Import bottled water
Wastewater Disposal	Sewage lagoons	Export off-site	Sewage lagoons	Export off-site
Solid Waste Disposal	Incineration	Landfill	Landfill	Incineration
EI	20.23	39.74	27.08	33.53
TC	$43,657.49	$110,643.58	$27,477.31	$115,717.41
	365-Day Duration			
	S31 (lowest EI)	S22 (highest EI)	S4 (lowest TC)	S33 (highest TC)
Energy Production	Solar Panels	BPUs	MEP-806s	Solar Panels
Potable Water Production	Import water tankers	Import bottled water	ROWPUs	Import bottled water
Wastewater Disposal	Sewage lagoons	Export off-site	Sewage lagoons	Export off-site
Solid Waste Disposal	Incineration	Landfill	Landfill	Incineration
EI	19.08	32.70	26.87	22.94
TC	$56,504.94	$64,408.93	$23,356.77	$78,390.41
	730-Day Duration			
	S31 (lowest EI)	S22 (highest EI)	S28 (lowest TC)	S21 (highest TC)
Energy Production	Solar Panels	BPUs	Solar Panels	BPUs
Potable Water Production	Import water tankers	Import bottled water	ROWPUs	Import bottled water
Wastewater Disposal	Sewage lagoons	Export off-site	Sewage lagoons	Export off-site
Solid Waste Disposal	Incineration	Landfill	Landfill	Incineration
EI	13.93	32.57	20.81	26.23
TC	$38,319.97	$62,419.69	$21,201.91	$64,804.67

Summary and Conclusions

This paper presented the development of a novel remote site sustainability assessment model capable of quantifying the environmental and economic performance of a set of infrastructure alternatives for remote communities. An application example of a hypothetical military FOB was evaluated over three durations in order to demonstrate the model's unique capability. The model was able to quantify the environmental and economic performance of 36 distinct combinations of infrastructure alternatives for each duration and identify tradeoffs between performance objectives. The evaluation of increasing site durations demonstrated that over time, high initial investments may be offset by low operating costs. This capability will enable construction planners to evaluate the impacts of their infrastructure alternatives in order to minimize environmental impacts while also minimizing costs. The scope of this model can be expanded with the identification of additional infrastructure alternatives. Additionally, sustainability indexes may be utilized in order to further develop this model into a robust optimization tool capable of optimizing remote site location, environmental impact, and cost.

IV. Scholarly Article 2: Optimizing the Environmental and Economic Sustainability of Remote Community Infrastructure

Jamie Filer, Justin Delorit, Andrew Hoisington, and Steven Schuldt

Abstract

Remote communities such as rural villages, post-disaster housing camps, and military forward operating bases are often located in remote and hostile areas with limited or no access to established infrastructure grids. Operating these communities with conventional assets requires constant resupply, which yields a significant logistical burden, creates negative environmental impacts, and increases costs. For example, a 2,000-member isolated village in northern Canada relying on diesel generators required \$8.6 million of fuel per year and emitted 8,500 tons of carbon dioxide. Remote community planners can mitigate these negative impacts by selecting sustainable technologies that minimize resource consumption and emissions. However, the alternatives often come at a higher procurement cost and mobilization requirement. To assist planners with this challenging task, this paper presents the development of a novel infrastructure sustainability assessment model capable of generating optimal tradeoffs between minimizing environmental impacts and minimizing life-cycle costs over the community's anticipated lifespan. Model performance was evaluated using a case study of a hypothetical 500-person remote military base with 864 feasible infrastructure portfolios and 48 procedural portfolios. The case study results demonstrated the model's novel capability to assist planners in identifying optimal combinations of infrastructure

alternatives that minimize negative sustainability impacts, leading to remote communities that are more self-sufficient with reduced emissions and costs.

Introduction

Remote communities such as rural villages, post-disaster housing camps, and military forward operating bases (FOB) are often detached from established infrastructure grids and require a constant resupply of resources. This resource dependence presents sustainability challenges such as a significant logistical burden, negative environmental impacts, and increased costs (Arriaga et al. 2014; Cave et al. 2011). In one example, a 2,000-member isolated village in northern Canada relying solely on diesel generators required 2.95 million liters of fuel per year to support its power requirement (Arriaga et al. 2013). The fuel cost $8.6M and emitted 8,500 tons of CO_2 – the annual equivalent of nearly 1,700 passenger vehicles.

For the purposes of this research effort, sustainability refers to the planning and implementation of conservation measures and infrastructure alternatives that reduce reliance on fossil fuels, conserve water, minimize waste streams, abate negative environmental impacts, and promote self-sufficient operations (Anderson et al. 2014). While this definition addresses only one portion of a broader sustainability challenge at remote communities, it enables the quantification and mitigation of negative environmental impacts and costs resulting directly from infrastructure decisions. Planners may choose to enhance the proposed objective function by adding measures of sustainability or adapting the function to be more reflective of the community in question. In the present application, power production, water production, and waste management systems are of primary concern due to their direct impact on sustainability objectives and logistical requirements for resources such as fuel, water, and waste (Akinyele and Rayudu 2016; Noblis 2010). Remote community planners have the opportunity to select technologies that will reduce negative sustainability impacts (IPCC 2014), but such alternatives are often bulky to transport and expensive to procure (Putnam et al. 2016). Both the environmental impact and cost involved with mobilizing equipment-based components can negatively impact sustainability objectives based on the item's size, weight, and mode of delivery. Accordingly, planners are faced with the challenging task of selecting infrastructure alternatives that optimize initial and operational tradeoffs between environmental and economic performance.

A number of studies have been conducted that (1) quantify the environmental impact of infrastructure; (2) identify tradeoffs between the environmental and economic impact of infrastructure alternatives; and (3) optimize tradeoffs between sustainability objectives for remote communities. First, various research efforts have quantified the environmental sustainability of infrastructure, including power production methods (Mao et al. 2013; WNA 2011; Xing et al. 2008); water production methods (Racoviceanu et al. 2007; Vince et al. 2008); wastewater management systems (El-Fadel and Massoud 2001; Toprak 1995); and solid waste management systems (Batool and Chuadhry 2009; Borglin et al. 2010; Zhao et al. 2009). These efforts quantified environmental sustainability through various indicators, such as greenhouse gas (GHG) emissions, pollution emissions, energy consumption, embodied emissions, and global warming potential. These indicators can be quantified at a static point in time, such as embedded emissions of materials, or over the infrastructure's lifetime via a life cycle assessment.

Second, additional studies identified tradeoffs between the environmental and economic sustainability of infrastructure alternatives. For example, Karatas and El-Rayes (2016) utilized GHG emissions, water consumption, and initial cost metrics to assess the integration of green building measures and fixtures into housing units, generating optimal tradeoffs between environmental impact and cost. Alternatively, Ozcan-Deniz et al. (2012) utilized a global warming potential (GWP) metric to optimize the selection of construction activities, thereby minimizing project time, cost, and environmental impact. Additional economic metrics include energy consumption, transportation requirements, operating costs, and life-cycle costs (Kamali and Hewage 2015).

Third, other research efforts optimized tradeoffs between sustainability objectives for remote communities. Optimization is the process by which one determines the best solution to a problem based on a set of constraints (Coello 2005). When this process includes just one objective, the intent is to determine one ideal solution. A multi-objective optimization problem, however, occurs when two or more objectives must be enhanced simultaneously. Often, these objectives are in direct conflict with each other, requiring the researcher to identify optimal tradeoffs between objectives. For example, El-Anwar et al (2010) identified infrastructure decision impacts on the prolonged use of isolated, post-disaster housing camps. The authors produced optimal housing construction decisions minimizing environmental, social welfare, economic, and public safety impacts. Conversely, Poreddy and Daniels (2012) and Putnam et al. (2016) analyzed military sites, investigating resource requirements as a proxy for sustainability. The first effort utilized a comprehensive systems-based approach to quantify a site’s resource requirements, such as electricity, fuel, water, maintenance hours, and geographical footprint. The authors proposed optimal site layouts that maximized operational efficiency and minimized logistical requirements. The second effort optimized the selection of infrastructure technologies to minimize mobilization investments and daily resupply. By quantifying the logistical impact of equipment and the volume of fuel, water, and waste transported on- and off-site each day, the work identified infrastructure alternatives that improved personnel safety and minimized transportation expenses. Filer and Schuldt (2019b) expanded Putnam's approach to quantify the impact of an infrastructure alternative's resource consumption and logistics on the environment. While the authors computed GHG emissions and total cost for various infrastructure systems, they failed to fully consider the impact of transportation requirements or establish optimal tradeoffs between competing objectives. This paper is a follow-on effort that expands transportation considerations, enhances emissions calculations, incorporates decision-maker priorities, and optimizes sustainability tradeoffs over time.

Despite the significant contributions of the aforementioned research studies, there has been no known research that has optimized sustainability in remote communities. That is, there lacks a detailed investigation that optimizes tradeoffs between the environmental and economic performance of remote community infrastructure alternatives while considering initial and recurring logistical requirements. To address this limitation, this paper presents the development of an innovative model that is capable of optimizing tradeoffs between the environmental and economic sustainability of remote community infrastructure.

The objective of this paper is to present an infrastructure sustainability assessment model that quantifies the tradeoffs between environmental impacts and life-cycle costs of remote communities. The model is intended to assist planners in the difficult task of analyzing and comparing all feasible combinations of infrastructure alternatives in order to construct sites with reduced costs, emissions, and resupply requirements. The following sections of this paper describe: (1) developing metrics to measure the performance of the model's two competing objectives; (2) formulating the model's objective function; (3) identifying the model's required input data; and (4) testing the model's performance via a case study.

Methodology

Decision Variables

The decision variables utilized in the present model are designed to represent feasible alternatives for enhancements to remote community infrastructure categories that impact sustainability objectives. The model considers various infrastructure alternatives, i, within infrastructure categories, j. The present model considers 11 infrastructure categories, including facility insulation, billeting, power production, water production, food preparation, refrigeration, laundry services, hygiene services, latrines, wastewater management, and solid waste management. These infrastructure categories were selected due to their direct impact on the key resource categories of fuel, water, wastewater, and solid waste. Each alternative is represented by an integer value, i. The model incorporates these alternatives into J infrastructure categories, where each alternative within category j fulfills the same support requirement. Site designers may select any one alternative per infrastructure category, so long as the same level-of-service constraint is achieved. A benefit of the model is its flexibility; it can be adapted for any number of infrastructure alternatives or categories.

For example, Figure 8 depicts the flexibility a planner has to select either an expeditionary or high efficiency latrine system alternative. One alternative must be chosen to meet the community's latrine requirement. The latrine infrastructure category is of concern due to its impact on all four resource categories, including fuel consumption, water consumption, wastewater production, and solid waste production.

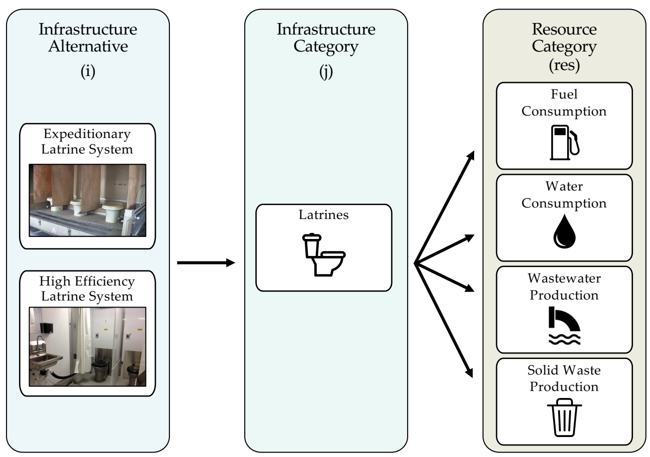

Figure 8. Example of decision variables impacting resource categories.

Metric Identification

The model was designed to minimize negative sustainability impacts by generating optimal tradeoffs between two competing objectives: (1) minimizing negative environmental impacts; and (2) minimizing life-cycle cost.

Environmental Impact Metric

The model's first metric is formulated to quantify the impact that remote community infrastructure has on the surrounding environment. While there are various approaches to quantifying environmental impact, greenhouse gas (GHG) emissions are of primary concern due to their influence on climate change. Of the GHGs, carbon dioxide (CO_2) is the largest direct source of radiative forcing from human activities, and it is, therefore, the baseline by which global warming potential is defined (Houghton et al. 1990; Reilly et al. 2001). The environmental impact of an infrastructure alternative over its lifespan is calculated as the sum of its initial environmental impact (IEI) and its ongoing daily environmental impact (DEI) (metric tons CO_2e). Accordingly, the environmental impact (EI_p) of a portfolio of alternatives is a summation of each alternative's EI, as shown in Equation (6). Each portfolio represents some combination of infrastructure alternatives where one alternative, i, is selected for each infrastructure category, j. The quantity of portfolios represents all possible combinations of alternatives, calculated as a product of the number of available infrastructure alternatives (I) within each infrastructure category (J).

$$minimize\ EI_p(t) = \sum_{j=1}^{J} \left(IEI_{ij} + tDEI_{ij} \right) \tag{6}$$

Where EI = environmental impact of infrastructure portfolio (tons CO_2e);

IEI = initial environmental impact of infrastructure alternative (tons CO_2e);

DEI = daily environmental impact of infrastructure alternative (tons CO_2e/day);

t = time (days);

i = infrastructure alternative;

j = infrastructure category;

J = total infrastructure categories; and

p = portfolio of alternatives: one alternative per infrastructure category.

An alternative's IEI accounts for the impact of its delivery to the site via air, rail, or sea as shown in Equation (7).

$$IEI_{ij} = r^{mode} w_{ij} d^{mode} \tag{7}$$

Where r = emissions rate of transportation mode (tons CO_2e/ton cargo/km) (Chao 2014);

mode = mode of transportation (air, land, or sea);

w = weight of infrastructure alternative (tons); and

d = transportation distance (km).

The DEI of infrastructure alternative i in category j may be calculated as a function of its daily impact due to each resource category and the resulting transportation requirement, shown in Equation (8). The resource categories of consideration are fuel consumption, water consumption, wastewater production, and solid waste production. The transportation requirement resulting from these resources is further complicated by the tendency of remote communities to utilize readily available, inefficient vehicles to transport resources on- and off-site at varying distances (d). Therefore, Equation (8) also accounts for fluctuations in vehicle capacity (c) and fuel economy (f).

$$DEI_{ij} = \sum_{res=1}^{4} \left(v_{ij}^{res} r_{ij}^{res} \right) + r^{fuel} \sum_{res=1}^{4} \left(\frac{v_{ij}^{res}}{c^{res}} \cdot \frac{d^{res}}{f^{res}} \right) \tag{8}$$

Where v = volume of resources (kg/day or L/day);

res = resources, 1: fuel, 2: potable water, 3: wastewater, and 4: solid waste;

r = emissions rate of resource (tons CO_2e/kg or tons CO_2e/L) (US EPA 2018);

c = carrying capacity of vehicle (kg or L); and

f = efficiency of vehicle transporting resources (km/L).

Cost Metric

The second metric was formulated to compute an infrastructure portfolio's life-cycle cost (C_p) from procurement through termination of operations via Equation (9).

$$minimize\ C_p(t) = \sum_{j=1}^{J}\left(IC_{ij} + tDC_{ij}\right) \tag{9}$$

Where C = life-cycle cost of infrastructure portfolio ($);

IC = initial cost of alternative ($); and

DC = daily cost of alternative ($/day).

An alternative's IC is a function of its procurement cost (PC) and the cost to transport it to the community's location, as shown in Equation (10) The transportation cost is dependent upon the operating cost (OC) of the transportation method and the number of trips required.

$$IC_{ij} = PC_{ij} + OC_{ij}^{mode} d_{ij}^{mode} \frac{w_{ij}}{c_{ij}^{mode}} \tag{10}$$

Where PC = cost to procure alternative or initiate service ($); and

OC = operating cost of transportation mode ($/mi);

While most infrastructure alternatives have an associated equipment procurement cost, many non-infrastructure alternatives do not. Rather, these have resource purchase costs and daily service fees. Therefore, an alternative's DC is computed as a function of daily service costs (SC) and resource transportation costs, as shown in Equation (11). Transportation costs are dependent upon the capacity (c) and efficiency (f) of the vehicle transporting each resource type, as well as the distance traveled (d). Further, cost structures are variable. Daily transportation costs may be considered separately, or they may be combined into the service cost. While the contract type shown here is relatively simple, planners have the ability to easily insert their own contract structures.

$$DC_{ij} = \sum_{res=1}^{4} \left(v_{ij}^{res} SC_{ij}^{res} \right) + SC^{fuel} \sum_{res=1}^{4} \left(\frac{v_{ij}^{res}}{c^{res}} \cdot \frac{d^{res}}{f^{res}} \right) \tag{11}$$

Where SC = service or purchase cost of resource ($/lb or $/gal).

Objective Function

Finally, minmax normalization is applied to the metrics from Equations (6) and (9) as shown in Equations (12) and (13), respectively. This action transforms sustainability metric data into unitless values ranging from zero to one, where zero represents the minimum EI or C of all available infrastructure portfolios and one represents the maximum. The normalizing function enables variables of dissimilar units to be computed into a unitless index.

$$EI_p^{norm}(t) = \frac{EI_p(t) - \min{(EI)}}{\max(EI) - \min{(EI)}} \tag{12}$$

$$C_p^{norm}(t) = \frac{C_p(t) - \min{(C)}}{\max(C) - \min{(C)}} \tag{13}$$

Where EI^{norm} = normalized environmental impact of an infrastructure portfolio; and

C^{norm} = normalized cost of an infrastructure portfolio.

Additionally, weights, wt_{EI} and wt_C, are identified to represent the priority a decision-maker places on each metric in the final optimization function. Both are represented by percentages which must sum to 100 percent. Finally, the objective function shown in Equation (14) is utilized to calculate an infrastructure portfolio's negative sustainability impacts, SI_p, and identify an optimal portfolio for any time t based on the decision-maker's priorities. For the purposes of this research effort, the optimal solution is defined as that portfolio which minimizes negative impacts on sustainability objectives.

$$minimize\ SI_p(t) = wt_{EI} EI_p^{norm}(t) + wt_C C_p^{norm}(t) \tag{14}$$

Where wt_{EI} = importance weight of environmental impact;

wt_C = importance weight of cost; and

SI = negative sustainability impacts of an infrastructure portfolio.

Model Input Data

Remote community planners must input a number of community features, planning factors, and infrastructure alternative characteristics, as outlined in Table 4. Community features describe the community's location and determine support requirements. Planning factor data establishes the site's total resource requirement, which is dependent upon location and number of personnel. Finally, feasible alternatives must be identified for each infrastructure category, such as power production, water production, wastewater management, solid waste management, etc. For each infrastructure alternative, characteristic data determines the alternative's resource consumption, waste production, transportation requirement, cost, and environmental impact. Life-cycle boundary conditions were implemented such that negative sustainability impacts were considered from the time of an alternative's mobilization through operation, while impacts from manufacturing and infrastructure retirement were excluded.

Table 4. Model input data.

Input Category	Inputs
Community Features	(1) required personnel (persons) (2) environment (e.g. desert, temperate, or tropical) (3) duration (days) (4) equipment delivery method (ground, air, or sea) (5) equipment delivery distance (km) (6) distance to local services (km) (7) transportation method efficiencies (km/L) (8) transportation method capacities (kg or L)
Planning Factors	(1) power consumption (kW/person/day) (2) potable water consumption (L/person/day) (3) solid waste production (kg/person/day) (4) wastewater production (L/person/day)
Infrastructure Alternative Characteristics	(1) fuel consumption (L/day) (2) water consumption (L/day) (3) wastewater production (L/day) (4) solid waste production (kg/day) (5) procurement cost (USD) (6) operating costs (USD) (7) shipping weight (kg) (8) emissions factor (ton CO_2/unit)

Case Study

In order to demonstrate the model, a theoretical military forward operating base (FOB) was designed as a reasonable representation of a remote community, and infrastructure alternatives were considered. A military application was chosen for the following example due to the abundance of bases with remote community characteristics and the breadth of data on sustainable base initiatives. For this case study, a baseline FOB was first modelled as a typical example of deployed military assets. Next, a set of equipment alternatives were modelled to demonstrate potential improvements as a result of investing in sustainable technologies. Then, a set of procedural alternatives were applied to demonstrate potential performance improvements based on currently fielded infrastructure.

For this case study, the required input data included community features, planning factors, and infrastructure alternative characteristics. First, community features were dictated based on the FOB's design to accommodate 300 personnel in an arid region of Southwest Asia for an anticipated duration of up to 7 years. All equipment technologies (such as generators, solar panels, and water purifiers) had to be delivered via aircraft from suppliers located in Central Europe, 5,150 km away. Common services (such as purchasing bottled water or contracting solid waste disposal) could be sourced from local vendors ranging from 40-80 km from the site. The community feature data and assumptions are summarized in Table 5. Second, planning factors were identified for power, water, wastewater, and solid waste through U.S. Army design manuals and historical data (Noblis 2010). Third, infrastructure alternative data was sourced from a collection of U.S. Army reports published as a result of an initiative to identify fuel, water, and waste (FWW) mitigation measures (Gildea et al. 2017b; a, 2018). Objectives were computed in R version 3.6.0 (R Core Team 2019) and figures were produced with the ggplot2 package (Hadley Wickham 2016).

Table 5. Case study community feature summary.

Resource	Variable	Value	Units	Reference
Fuel	Cost (SC^{fuel})	4	$/L	(Noblis 2010)
	Emissions Rate (r^{fuel})	2.6×10^{-3}	metric tons CO_2/L	(US EPA 2018)
	Delivery Distance (d^{fuel})	65	km	
	Vehicle Efficiency (f^{fuel})	0.8	km/L	[34]
	Vehicle Capacity (c^{fuel})	18,925	L	(Oshkosh 2020)
Water	Cost (SC^{water})	2.6	$/L	(Noblis 2010)
	Delivery Distance (d^{water})	40	km	
	Vehicle Efficiency (f^{water})	0.7	km/L	(Oshkosh 2020)
	Vehicle Capacity (c^{water})	17,033	L	(Oshkosh 2020)
Wastewater	Cost (SC^{ww})	0.5	$/L	
	Emissions Rate (r^{ww})	2.3×10^{-5}	metric tons CO_2/L	
	Delivery Distance (d^{ww})	80	km	
	Vehicle Efficiency (f^{ww})	0.7	km/L	(Oshkosh 2020)
	Vehicle Capacity (c^{ww})	15,140	L	(Oshkosh 2020)
Solid Waste	Cost (SC^{sw})	8.8	$/kg	
	Emissions Rate - landfill (r^{sw})	1.3×10^{-3}	metric tons CO_2/kg	(Cherubini et al. 2009)
	Emissions Rate - burn pit (r^{sw})	9.9×10^{-4}	metric tons CO_2/kg	
	Emissions Rate - incinerator (r^{sw})	6.4×10^{-4}	metric tons CO_2/kg	(Cherubini et al. 2009)
	Delivery Distance (d^{sw})	72	km	
	Vehicle Efficiency (f^{sw})	0.7	km/L	(Oshkosh 2020)
	Vehicle Capacity (c^{sw})	16.5	tons	(Oshkosh 2020)
Equipment Alternatives	Cost (OC^{air})	29	$/km	(Ritsick 2019)
	Emissions Rate (r^{air})	4.1×10^{-4}	metric tons CO_2/km	(Chao 2014)
	Delivery Distance (d^{air})	5,172	km	
	Aircraft Capacity (c^{air})	86	tons	(Ritsick 2019)

Baseline

First, a set of baseline FWW values, summarized in Table 6, was established through experimental testing of a baseline camp setup (Harris et al. 2017). This baseline established a standard by which all other alternatives could be compared. The baseline setup represented commonly deployed assets for billeting, food preparation and dining facilities, hygiene services, waste management, water storage and distribution, and power generation, as shown in Table 7. The identified fuel demand included fuel for infrastructure sustainment only – fuel required for transportation outside of the FOB must be accounted for separately. Historical data and subject matter expertise ensured that the baseline infrastructure met U.S. Army requirements for sustainment of a 300-person contingency site.

The FOB's baseline environmental impact and cost were calculated, using Equations (6-8). The initial environmental impact was found to be 2,350 tons CO_2e, increasing at a rate of 14.3 tons/day. The capital procurement and mobilization cost was $3.1M with operating costs of $134,000/day. These values provide a standard by which further infrastructure alternatives may be compared.

Table 6. Resource summary, 300 personnel, arid environment (Gildea et al. 2017b).

Resource Category	Volume	Unit
Fuel Demand	3,944	L/day
Power Demand	5,108	kWh/day
Potable Water Demand	33,017	L/day
Wastewater Demand	32,282	L/day
Solid Waste Demand	1,302	kg/day

Table 7. Equipment and procedural infrastructure alternative characteristics.

	Infra. Cat.	Alternative	Fuel Consumpt. (L)	Power Consumpt. (kWh)	Potable Water Consumpt. (L)	Wastewater Production (L)	Solid Waste Production (kg)	Shipping Weight (kg)	Purchase Cost ($/unit)
Equipment Alternatives		Baseline site	3,944	5,108	33,017	32,282	1,302	506,835	$ 1,191,215
	Facility Insulation	(Baseline Alternative) - Single ply tent liner						3,129	$ 23,000
		Insulated tent liner and photovoltaic array shade	3,478	2,800	33,017	32,282	1,302	17,647	$ 487,830
	Power Production	(Baseline Alternative) - 60 kW tactical generator						41,929	$ 650,000
		Hybrid generator and battery system	2,740	5,108	33,017	32,282	1,302	241,061	$ 7,200,000
		Photovoltaic array and battery system	397	5,108	33,017	32,282	1,302	1,015,840	$ 35,600,000
	Food Preparation	(Baseline Alternative) - Expeditionary kitchen system						6,349	$ 150,000
		Fuel-fired expeditionary kitchen system	3,823	4,876	33,304	32,570	1,302	6,984	$ 170,000
	Refrigeration	(Baseline Alternative) - Multi-temperature refrigeration system						18,225	$ 120,000
		High efficiency refrigeration system with solar array	3,914	4,963	33,017	32,282	1,302	17,493	$ 136,150
	Water Production	(Baseline Alternative) - Bottled water imported to site						0	$ -
		Reverse osmosis water purification system	4,148	5,397	-4,349	32,282	1,302	3,628	$ 284,500
	Latrines	(Baseline Alternative) - Expeditionary latrine system						11,646	$ 200,000
		High efficiency latrine system	4,383	5,256	25,401	23,020	1,305	13,393	$ 240,000
	Solid Waste Management	(Baseline Alternative) - Waste exported from site to landfill						0	$ -
		Open-air burn pit	4,020	5,108	33,017	32,282	160	0	$ 5,000
		Incinerator	4,008	5,169	33,017	32,282	226	38,774	$ 750,000
	Wastewater Management	(Baseline Alternative) - Waste exported from site						0	$ -
		Activated sludge bioreactor	3,952	5,152	33,017	3,452	1,302	12,898	$ 400,000
		Activated sludge bioreactor and reverse osmosis water purification system	3,963	5,189	15,806	1,768	1,302	22,571	$ 1,150,000
Procedural Alternatives	Billeting	(Baseline Alternative) - 14 personnel per tent						425,292	$ 45,885
		Billeting consolidation, 18 personnel per tent	3,732	4,603	33,017	32,282	1,302	402,436	$ 35,910
	Power Production	(Baseline Alternative) - 60 kW tactical generator						38,704	$ 600,000
		Generator reallocation according to average loading	3,168	5,108	33,017	32,282	1,302	27,415	$ 425,000
		60 kW tactical generator grid	2,324	5,108	33,017	32,282	1,302	40,316	$ 625,000
	Laundry Services	(Baseline Alternative) - Unlimited laundry allowance						261	$ 2,250
		1/2 baseline laundry allowance	3,921	5,007	31,597	32,282	1,302	156	$ 1,350
	Hygiene Services	(Baseline Alternative) - 10-minute daily showers						4	$ 80
		7-minute weekly showers	3,876	5,085	17,998	17,260	1,302	4	$ 80
	Latrines	(Baseline Alternative) - Unlimited toilet flushes						11,646	$ 200,000
		Reduced toilet flushes	3,936	5,103	27,634	26,900	1,302	11,646	$ 200,000

Equipment Alternatives

Next, the performance of a set of equipment alternatives was modelled. The alternatives and their FWW consumption and production values are detailed in Table 7 as compared to the baseline. The results of this analysis are shown in Figure 9. Each alternative required some material equipment in addition to, or in place of, a baseline equipment set with the potential to conserve resources. Coincidentally, many of these technologies required a substantial investment in terms of the purchase cost and delivery. For example, a photovoltaic array and lithium ion battery system, as a power production alternative, was compared against a baseline of 60 kW generators. While the solar alternative saved the site nearly 3,560 liters of fuel per day, the equipment itself weighed over 900,000 kg more than its generator competitor (Thomsen et al. 2019). This extra weight imposed additional delivery costs and transportation emissions.

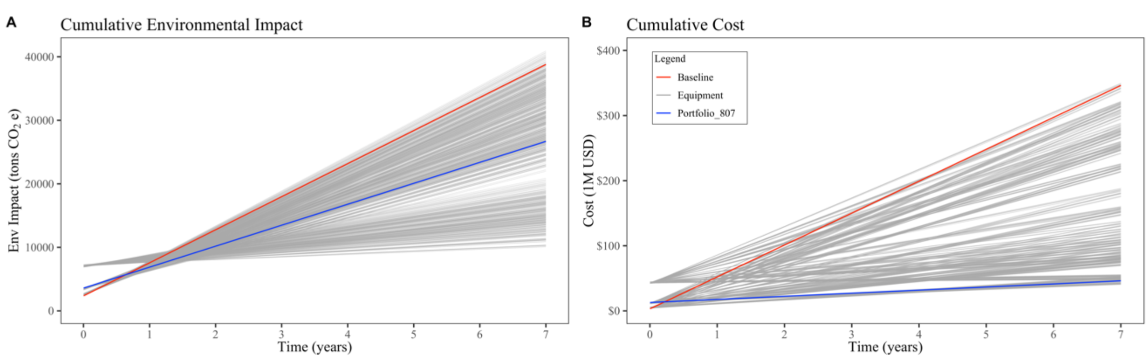

Figure 9. The initial impact of alternatives may be offset by low operating requirements.

Figure 9 illustrates the tradeoffs between initial and operating requirements for 864 potential equipment portfolios. Each line represents the cumulative EI and C of one portfolio, with the baseline signified in red. While the baseline equipment set imposed a low IEI and IC, it led to one of the highest possible cumulative EI and C values due to its operating requirements. Other alternatives imposed higher IEI and IC values but lower operating requirements. For example, portfolio #807, shown in Figure 9 as a blue line, was comprised nearly exclusively of sustainable technologies outlined in Table 8. While this portfolio's IEI and IC were 1.5 and 4.2 times higher than the baseline's, its operating requirements were 1.6 and 10.3 times lower, respectively. These sustainability tradeoffs resulted in the IC being offset after 81 days and the IEI being offset after 231 days, at which time portfolio #807 became more sustainable than the baseline. Similarly, each interaction in Figure 9 designates the time at which a portfolio became a more environmentally or financially sustainable choice.

Table 8. Baseline versus portfolio #807, an example of sustainable equipment alternatives.

Infrastructure Category	Baseline	Portfolio #807
Fac. Insulation	Single ply tent liner	Single ply tent liner
Power Pro.	60 kW tactical generator	Hybrid generator and battery system
Food Prep.	Expeditionary kitchen system	Expeditionary kitchen system
Refrigeration	Multi-temperature refrigeration system	High efficiency refrigeration system with solar array
Water Pro.	Bottled water imported to site	Reverse osmosis water purification system
Latrines	Expeditionary latrine system	Expeditionary latrine system
Solid Waste Mgmt.	Waste exported from site to landfill	Incinerator
Wastewater Mgmt.	Waste exported from site	Activated sludge bioreactor and reverse osmosis water purification system
Initial EI (CO_2e)	2,356	3,581
Daily EI (CO_2e)	14	9
Initial C ($)	$3,100,000	$12,900,000
Daily C ($)	$134,000	$13,000

Procedural Alternatives

In addition to the 864 equipment portfolios, 48 procedural portfolios were also identified through the U.S. Army's FWW initiative, shown in Table 7 and Figure 10. While the equipment alternatives considered deviations from existing infrastructure, the procedural alternatives utilized only baseline camp equipment. The assessed procedures instead aimed to mitigate resource consumption by restricting personnel quality of life allowances, such as shortening shower times or limiting loads of self-help laundry. For this portion of the case study, each feasible portfolio was comprised of a unique combination of procedural alternatives and evaluated against the baseline. Portfolio #48, the most sustainable set of procedural alternatives, is designated in Figure 10 by a green line. Portfolio #48 was comprised exclusively of resource-saving measures such as billeting consolidation, limited laundry allowances, and reduced shower times and toilet flushes. While these alternatives were not considered in the final optimization function, they did highlight the model's ability to quantify potential sustainability improvements with limited equipment investment.

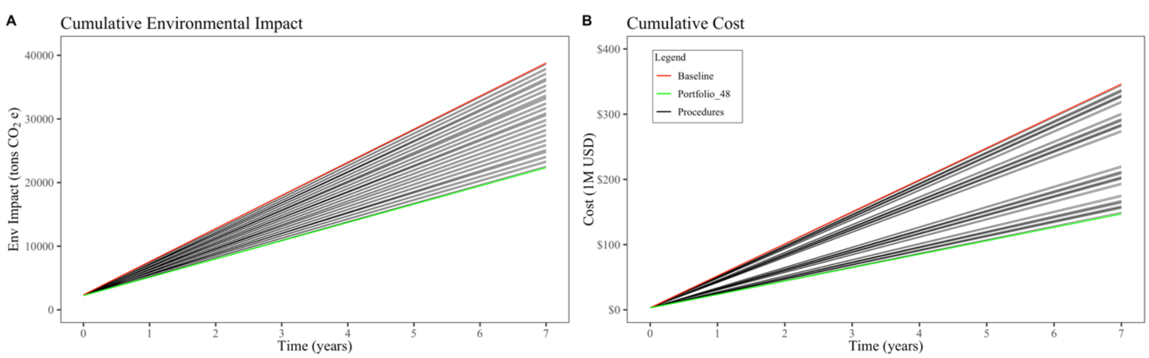

Figure 10. Procedural alternatives result in lower environmental impacts and costs due to negligible investment requirements.

Optimal Alternatives

Finally, the equipment alternative data was normalized, and the negative sustainability impacts (SI_p) of all equipment-based portfolios were calculated. Then, the optimal solution with the lowest SI at each point in time was identified. Figure 11 shows optimal portfolios for varying importance weights with the baseline in red for comparison.

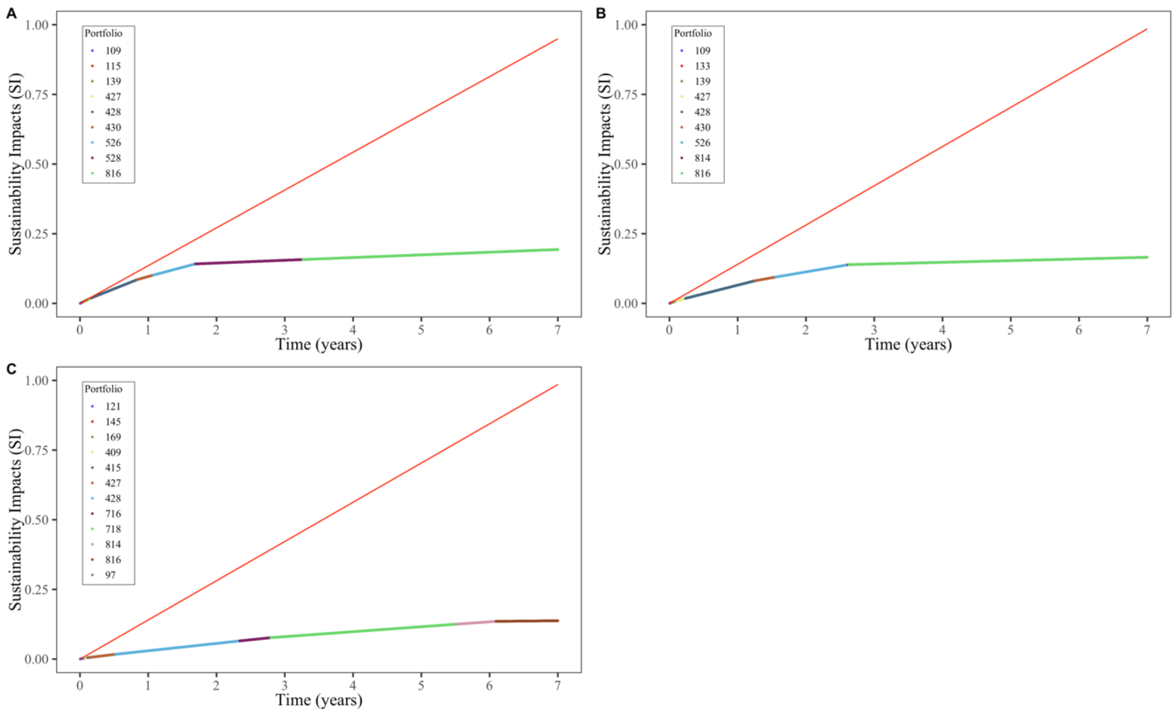

Figure 11. Optimal portfolios according to varying importance weights: (a) wt_{EI}=90%, wt_{C}=10%; (b) wt_{EI}=50%, wt_{C}=50%; and (c) wt_{EI}=10%, wt_{C}=90%.

In each scenario, the optimal site makeup transitioned rapidly over the first three years. After this point, the optimal site began to steady. In Figs. 11a and 11b, the importance weight applied to the environmental impact was set at 90% and 50%, respectively. In both scenarios, portfolio #816 was found to be the optimal infrastructure alternative combination from 3 years on due to its low daily emissions of 1.1 CO_2e/day. This site's makeup included sustainable technologies such as photovoltaic arrays and high efficiency refrigerators and incinerators, as described in Table 9. Figure 11c, however, illustrates optimal solutions when the environmental impact importance weight was set at just 10%. In this scenario, the optimal alternative combination changed twice in the fifth year before settling on portfolio #97. Rather than including pricey, environmentally conscious technologies, this site relied on less expensive, easily transportable alternatives that resulted in low procurement and operating costs.

Table 9. Optimal equipment portfolios according to varying importance weights.

Infrastructure Category	Portfolio #816	Portfolio #97
Fac. Insulation	Insulated tent liner and photovoltaic array shade	Single ply tent liner
Power Pro.	Photovoltaic array and battery system	60 kW tactical generator
Food Prep.	Fuel-fired expeditionary kitchen system	Expeditionary kitchen system
Refrigeration	High efficiency refrigeration system with solar array	Multi-temperature refrigeration system
Water Pro.	Reverse osmosis water purification system	Bottled water imported to site
Latrines	Expeditionary latrine system	Expeditionary latrine system
Solid Waste Mgmt.	Incinerator	Open-air burn pit
Wastewater Mgmt.	Activated sludge bioreactor and reverse osmosis water purification system	Waste exported from site
Initial EI (CO_2e)	7,253	2,356
Daily EI (CO_2e)	1	14
Initial C ($)	$44,730,000	$3,100,000
Daily C ($)	$1,500	$123,000

Summary and Conclusions

This paper presented a novel infrastructure sustainability assessment model for the design and construction of remote communities. The model was developed in four main sections that included: (1) developing metrics to measure the environmental and economic performance of infrastructure alternatives; (2) formulating the model's objective functions; (3) identifying the model's required input data; and (4) testing the model's performance via a case study. The case study modelled 864 portfolios of feasible infrastructure alternatives and 48 portfolios of procedural alternatives, highlighting that the model is capable of quantifying sustainability impacts for a wide range of decision-maker priorities and infrastructure alternatives. The results also display the model's effectiveness at identifying the environmental and economic tradeoffs associated with more sustainable, yet more bulky and costly, alternatives. The model was able to generate optimal portfolio solutions according to the importance a planner assigns to the environmental impact and cost metrics. This model has the potential to assist planners by allowing them to identify optimal infrastructure alternatives according to the remote community's mission, location, and personnel requirements.

This paper presents a model that may be utilized as a framework into which additional sustainability objectives can be incorporated. In this work, the objectives of environmental impact and cost assess the sustainability of infrastructure portfolio decisions, investigating impacts on resource consumption and transportation requirements. While the framework does provide a conduit through which the sustainability of infrastructure systems can be optimized for remote communities, the model presented here is not exhaustive, and future research is necessary. Areas of future research include the optimization of geographical citing according to resource locations, the ability to select multiple alternatives within each category in order to realize synergistic benefits, and the incorporation of additional sustainability objectives such as quality of life, social impact, and human health. Additionally, the present model assumed constant daily resource requirements and emissions factors. Further research should consider a more robust analysis of emissions and operating costs to account for equipment deterioration and irregular maintenance requirements. Additionally, while the presented objective function accounted for the environmental impact and cost from an infrastructure alternative's purchase through operation, it disregarded production and demolition. Here, it was assumed that all infrastructure alternatives were previously manufactured, which classified their economic impacts as sunk costs. And because the remote community's duration was flexible, the impacts due to demolition or reconstitution were considered negligible. The present model may be adapted to account for these factors.

V. Conclusions and Recommendations

Research Conclusions

This thesis focused on evaluating and optimizing the selection of infrastructure to maximize the sustainability of contingency bases. Accordingly, this effort aimed to accomplish three primary research objectives:

1. Conduct a comprehensive review of the current body of literature surrounding infrastructure sustainability practices and logistical impacts associated with contingency base infrastructure.
2. Identify and quantify the tradeoffs between environmental and economic sustainability objectives for contingency base infrastructure alternatives.
3. Develop and implement a novel infrastructure sustainability assessment model capable of optimizing the tradeoffs between environmental and economic performance of infrastructure alternatives.

First, a review of current literature on sustainability practices and contingency base logistical challenges was completed in Chapter 2. In this chapter, infrastructure sustainability was evaluated in three parts, each building off the last: environmental sustainability of infrastructure, environmental and economic sustainability of infrastructure, and environmental and economic sustainability of contingency base infrastructure. While the environmental impact of infrastructure may be accounted for through various measures, the literature revealed equivalent greenhouse gasses (volume of CO_2e) to be the most commonly accepted metric. Further, the infrastructure types most directly impacting sustainability objectives were power production, potable water production, wastewater management, and solid waste management. For economic sustainability, a life-cycle assessment was found to be the most comprehensive and accurate approach.

The second objective was accomplished in Chapter 3, "Quantifying the environmental and economic performance of remote communities." This paper presented a methodology to quantify the environmental and economic sustainability of remote community infrastructure. The model measured resource inputs and outputs for the primary infrastructure categories of power production, water production, wastewater management, and solid waste management, and identified tradeoffs between the competing objectives. Through a 500-person FOB application example, the model demonstrated the potential for high infrastructure investments to be offset by low operating costs. This paper was presented at the 7th International Conference on Sustainable Development in September 2019 (Filer and Schuldt 2019a) and published in the European Journal of Sustainable Development in October 2019 (Filer and Schuldt 2019b).

The third research objective was addressed in Chapter 4, "Optimizing the environmental and economic performance of remote community infrastructure." This paper presented the development of a novel infrastructure sustainability assessment model capable of optimizing tradeoffs between the competing objectives of minimizing environmental impacts and minimizing costs. Expanding upon the advances made in Chapter 3, this paper provides planners with a tool capable of identifying, from a set of feasible alternatives, optimal combinations of infrastructure technologies that minimize logistical requirements, emissions, and life-cycle costs. Model performance was evaluated through a hypothetical case study for a 500-person FOB with a search space of 912 potential solutions. The resulting solutions demonstrated the model's effectiveness at optimizing the environmental and economic tradeoffs associated with implementing more sustainable, yet more bulky and costly, alternatives. This paper is intended for publication in MDPI's Sustainability Journal, an international, peer-reviewed publication with an impact factor of 2.592.

Research Contributions

The primary research contributions of this thesis include the development of:

1. New metrics capable of quantifying the environmental and economic performance of infrastructure alternatives at contingency bases.
2. Novel analytical formulas for evaluating the environmental impact and cost of mobilizing infrastructure alternatives and resources to a contingency base.
3. An original objective function capable of optimizing the design of contingency base infrastructure that provides the unique capability of generating optimal tradeoffs between minimizing environmental impacts and minimizing life-cycle costs.

Research Impact

The aforementioned research contributions are expected to have significant impacts on the current practices for designing and constructing contingency sites. This thesis is the first effort to maximize contingency base sustainability by presenting two novel assessment models capable of identifying and optimizing tradeoffs between the competing objectives of environmental impacts and life-cycle costs. These models have the potential to guide future basing decisions by providing decision-makers with quality information regarding the sustainability of infrastructure alternatives. This thesis laid the groundwork for follow-on research efforts currently underway at the Air Force Institute of Technology. Furthermore, this thesis culminated in the development of two journal papers, one conference presentation, and two poster exhibitions, enhancing the academic and military community's awareness and knowledge of the present subject matter.

Recommendations for Future Research

This thesis was impacted by data availability, which led to a limited portfolio of infrastructure alternatives. As the DoD continues to explore sustainable technologies, future research efforts could expand this portfolio to include additional equipment and non-equipment infrastructure alternatives in order to generate more comprehensive models of contingency base sustainability. In order to support future modeling efforts, technological alternative data should include resource consumption, waste production, size, weight, purchase cost, maintenance and operating costs, and manpower requirements.

Second, this thesis primarily focused on two of the three tenets of sustainability, environmental, and economic performance. Future research efforts have the opportunity to develop social or human-impact metrics to complete the triad and expand the developed models into multi-objective optimization models with three competing objectives. With an expanded dataset and inclusion of additional metrics, further research will likely require advanced computing techniques such as genetic algorithms.

Finally, additional research could focus on the optimization of contingency base siting based on a region's terrain, availability of resources, existing bases, and mission requirements. A siting model could utilize the method of resource accounting presented in this thesis, coupled with geographical optimization techniques, to determine the optimal number and location of contingency bases to meet combatant commander objectives.

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14. ABSTRACT

Contingency bases are often located in remote areas with limited access to established infrastructure grids. This isolation leads to standalone systems comprised of inefficient, resource-dependent infrastructure, which yields a significant logistical burden, creates negative environmental impacts, and increases costs. Planners can mitigate these negative impacts by selecting sustainable technologies. However, such alternatives often come at a higher procurement cost and mobilization requirement. Accordingly, this study aims to develop and implement a novel infrastructure sustainability assessment model capable of optimizing the tradeoffs between environmental and economic performance of infrastructure alternatives.

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