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Decision Model for Additive versus Conventional Construction in Remote Locations

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DECISION MODEL FOR ADDITIVE VERSUS CONVENTIONAL CONSTRUCTION IN REMOTE LOCATIONS

THESIS

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Abstract

Additive construction is a potential game changing innovative alternative to conventional methods with regards to structural integrity, timeliness, and waste reduction, especially in remote locations. While there have been numerous studies into the material science, additive construction will not be a viable alternative until a cost analysis is performed. This paper details the cost elements for both methods. Breaking down the key variables of material, logistics and transportation, and labor costs garners a better understanding of the cost difference between the two construction methods. To assist decision-makers, this thesis compiles the factors that lead to the construction cost and provides a model that allows for selecting the optimal method for their specific project. To demonstrate the model, two real-world case studies verified the capabilities, while a discussion showcased the application and versatility. A sensitivity analysis of the site distance accompanies each case study to reveal at which distance the optimal method changes. For small construction projects at a distance, conventional construction methods were more cost-effective due to the overwhelming transportation cost. Results show that as the project size increases, the cost savings between the material and labor factors supersede the transportation cost, making additive construction the optimal construction method. This research helps decision-makers answer the question of which method is more cost-effective for a unique construction project. However, this research is considered exploratory and should not be used for decision-making without further analysis.

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DECISION MODEL FOR ADDITIVE MANUFACTURING VERSUS CONVENTIONAL CONSTRUCTION IN REMOTE LOCATIONS

I. Introduction

The construction industry is one of the world's largest economic sectors, though it is often perceived as non-innovative (Davis et al., 2016). Current construction methods have changed little over the past hundred years and have become stagnant, not keeping up with global productivity; however, the growing customer and economic demands desire more innovative methods (Bock, 2015; Davis et al., 2016). Additive Manufacturing (AM) is one of the innovative emerging trends. Also known as 3D-printing, AM typically involves heating metals and plastics to a melting point and manipulating the liquid to build a component. Additive manufacturing technology is ideal for prototyping and equipment maintenance because it can produce parts on-site efficiently. In the past 20 years, engineers examined this technology and attempted to replicate its success in the construction industry. Unlike the original technology creating small prototypes, engineers try to build large structures as a construction substitute. Today, additive manufacturing feasibility is a viable, cost-effective construction method that challenges how buildings are built (Jagoda et al., 2020).

Background

Additive manufacturing is a rapidly growing, young field. 3D printers are similar to traditional laser printers, but rather than using ink, the 3D image is built layer by layer. A nozzle extrudes a liquid that travels along a predetermined path. Typical component printing uses plastics or metals heated to a melting point. The melted material is extruded

onto the path and cooled to its solid form before the next layer arrives. Computer software sets a track to follow by providing the printer X, Y, and Z coordinates, so the printer knows exactly where to go (Lin et al., 2018). This process was patented in 1996 by Behrokh Khoshnevis (Khoshnevis, 1996), who is often referred to as the “father of large-scale printing” (Krassenstein, 2015).

Before 1996, construction used human power to pour concrete, erect structures, and install components. With computer technology and automation progression, emerging technologies may provide a more efficient way to construct buildings. This trend creates the term additive construction (Labonnote et al., 2016), which is an emerging technology that allows machines to manipulate concrete to create freeform structures layer-by-layer (Al-Qutaifi et al., 2018; Lin et al., 2018). Unlike the AM methods for plastics and metals, printed construction uses a piped nozzle system to mix the cementitious dry material with water and extrudes the paste, mortar, or concrete mixture in place. As such, there is no need for large cement trucks or wood forms.

The additive construction process uses fewer materials and personnel with higher efficiencies to build these structures, making it ideal for budget-constrained environments (Papachristoforou et al., 2018; Al-Qutaifi et al., 2018). Remote construction sites are examples of budget-constrained environments. These sites typically have limited support systems for personnel and require large amounts of travel to obtain materials for construction projects. The distance between the project location and a local material source creates an additional cost with construction supplies. This situation is a prime example of how additive construction may have an advantage over conventional construction.

The potential for cost savings has garnered the attention of the United States Army. In 2015, the U.S. Army Engineer Research and Development Center Construction Engineer Research Laboratory (ERDC-CERL) established the Automated Construction of Expeditionary Structures (ACES) program. The goal of ACES is to provide custom-designed structures with minimal personnel, time, and materials (ACES, 2019). Together with the United States Air Force, Navy, and Marines, the ACES program has printed barracks, entry control points, bridges, and other expeditionary structures (ACES, 2019; Diggs-McGee et al., 2019; Kreiger et al., 2019). The development of the program led to the question of viability in contingency environments compared to conventional construction. The Air Force Civil Engineer Center led that inquiry by sponsoring research to determine the viability of additive construction as a method of temporary and permanent construction. The investigation found seven viability factors for the use of additive construction: materials, structural design, efficiency, environmental impact, labor, logistics, and cost (Jagoda et al., 2020).

A breakdown of the seven factors guides the direction for this research. There is significant research in material science because, in additive construction, the materials are more physically sensitive due to pumpability. Optimizing the materials leads to the second viability factor regarding how to place the materials. The structural design gives additive construction an increase in design freedom due to the lack of formwork and increased flexibility. Although, additive construction lacks codes and standards, being such a relatively new construction technique. The optimized material and structural design freedom give the ability to print structures with minimal downtime for cleaning and maintenance. This freedom creates a higher level of efficiency with less material

waste and energy consumption. An efficient additive construction system generates a lower environmental impact compared to conventional construction. In addition to reducing material and energy consumption, the labor demand for additive construction is minimal. Additive construction shows potential cost savings of up to 40% in labor demands over conventional construction (Kreiger et al., 2019). Logistics is another viability factor addressed by additive construction. The logistical consideration is reduced because of minimal material requirements, thus shortening the supply chain and material delivery costs. The final viability factor to consider is the cost. While the viability investigation directs further research for all aspects, cost has a comprehensive uncertainty affecting other elements that requires additional analysis (Jagoda et al., 2020).

Unfortunately, the question of which construction method is cheaper is not as easy as comparing "apples to apples." Research finds that the materials used for additive construction differ from conventional construction methods (Rushing et al., 2019). The additive construction materials need to be extruded from the printer while maintaining the layer shape and not collapsing under its weight or the layers above it (Papachristoforou et al., 2018; Al-Qutaifi et al., 2018). Therefore, the materials used for additive construction need to be considered separately from conventional construction method materials. The cost of these materials and the necessary transportation methods to get the materials on-site need to be individually considered to see which way is optimal for construction projects at each unique remote location. Additionally, labor costs account for over 55% of the typical conventional construction project's total cost (Kreiger et al., 2019). Determining the cost of the labor for each construction method has a direct impact on the cost variation between the two processes.

The transportation cost relies on many factors. For example, aircraft have different cargo capacities, cruising speeds, and costs per flight hour in a military contingency environment. The size of the construction project will determine the amount of material transported. The volume and weight of the transported material will dictate the type and quantity of aircraft. This cargo issue also applies to ground transportation. Not all trucks are the same; some are standard pickup trucks, while others are large commercial 18-wheelers.

Labor cost is also a significant portion of the overall project cost and contains substantial uncertainty. The external factors that create uncertainty within the labor costs include temperature variance and structural complexity. An increase in temperature and an increase in complexity negatively affect worker productivity, thereby causing a significant expense increase (Li et al., 2016; Moohialdin et al., 2019). Minimizing labor can reduce this uncertainty.

The uncertainty in the material weights, the vehicle, and labor make it difficult to clearly state which construction method is optimal. Previous research has focused on the appropriate materials and techniques for additive construction to be a valid process. However, comparing additive to conventional construction methods did not consider the combined material, logistics and transportation, and labor costs in the past.

Problem Statement

The cost associated with additive construction is a crucial component of using it as a construction method. ERDC-CERL has been focusing on developing the most suitable material; however, they have received frequent inquiries regarding the cost

compared to conventional construction. Decision-makers want to know the price, but there are many variables that need to be addressed. This research investigates the use of a potential model to answer which construction method is most appropriate. The costs in question are the material, logistics and transportation, and labor costs associated with each process. There are no existing studies to determine which construction method is the most cost-efficient in any environment incorporating transportation and logistics. This research provides a decision-making model to give decision-makers a tool to define which construction method is optimal for their specific project.

Research Questions

This research intends to provide a cost analysis between additive and conventional construction methods. Given this intent, the research question states, "How can cost variables be consolidated and compiled to give a cost comparison decision-making tool between additive and conventional construction?" The answer to the overarching question requires investigating the following questions.

1. What are the most critical variables driving the cost of construction projects?
2. How do critical variables differ between additive and conventional construction projects?
3. How does the location affect the cost of the project and the construction method decision?
4. How do additive and conventional construction costs vary under different scenarios?

Answering these questions will provide information into specific areas when comparing each construction method. This research examines two case studies to answer the

investigative questions. These answers will provide decision-makers with a more comprehensive approach to the costs associated with constructing a new structure.

Methodology

Past research finds variables in materials, transportation, and labor to be critical factors in construction costs (Díaz et al., 2015; Diggs-McGee et al., 2019; Kreiger et al., 2019; Rushing et al., 2019). An equation combines these factors to determine a cost estimate for each construction method. The common elements between the two equations are the distance of the local source of material and the source airport from which material originates. The quantities and volumes differ based on the construction method.

ERDC-CERL provides the material and labor variables for additive construction. Two past projects generated the material and labor costs and quantities for additive construction; they also guided the estimation of transportation costs for the material and equipment. The labor hour cost was consistent with hourly wages for equipment operators of the same type of machinery. Similar structure costs using conventional construction methods were estimated using the RS Means, the industry-accepted cost estimating software, to provide an accurate comparison.

The logistical information needed for this study encompasses air and ground transportation, labor, and material requirements. Unclassified documents from Air Force publications show aircraft data. Ground transportation varies based on the vehicles; therefore, information gathered from commercially available data represents typical vehicles and does not consider all possible options. The fuel efficiency, in conjunction

with the distance and fuel cost, provides a transportation cost. Additionally, the volume capacity when compared to the requirements will give the needed vehicle quantity. The total cost estimate of each construction method was combined and compared.

Assumptions/Limitations

One of the significant drawbacks to AM is the lack of full construction automation. Additive construction will only replace part of the traditional building process until technology overcomes the challenges (Al-Safy, 2019). There is still a requirement for component support to include installing windows, doors, plumbing, electrical systems, and other support systems (Zhang, 2013). The comparison in this research only examines the shell of the structure.

Currently, the COVID-19 pandemic limits the amount of research performed. The information gathered relies on past additive construction projects. This information includes the material weights and costs previously used at the market value paid at the time of construction. The lack of in-person contact limits the quantity of additional information that may bolster arguments further.

Significance of Study

As previously stated, there are seven viability factors for the use of additive construction: materials, structural design, environmental impact, efficiency, labor, logistics, and cost (Jagoda et al., 2020). The key viability factors investigated as part of this research are material, logistics, and labor, as they are significant in the analysis between using additive construction over conventional construction methods. This research will help decision-makers choose which construction method is the most cost-

effective for a specific project. The cost analysis will also encourage future research to incorporate weight, transportation, and labor costs into their material designs. This research is considered exploratory and should not be used for decision-making without further analysis.

Preview of Remaining Chapters

This thesis follows a traditional format. Chapter II includes a literature review of the subjects in question, which aims to guide the reader into previous research that has molded the current state of additive construction. Previous studies also considered the cost effects of materials, transportation, and labor on the overall project costs. Chapter III provides a discussion of the methodology to develop the model. Throughout Chapter III, the reason for each question being asked, each piece of information gathered, and how it applies to the expected result is displayed clearly. Data is collected from Air Force Instruction documents, industry-accepted cost estimating software, commercial cost documents, and historical data from past projects. The information obtained in the methodology is analyzed in Chapter IV, Analysis and Results. This chapter compiles all data points into a single model for decision-making. The model will evaluate multiple case studies to showcase construction method differences. Finally, Chapter V provides the conclusions and recommendations resulting from the research, expands on the research's significance, and discusses potential follow-up research opportunities.

II. Literature Review

The purpose of this chapter is to provide a literature review of relevant past research. The chapter provides the history of additive construction, then discusses research comparing additive and current construction techniques. The comparison is through the following factors: materials, logistics and transportation, and labor. Following the comparative analysis of these three elements is a review of decision-making models and their applicability to this research. The combination of the labor risk and cost reduction, the minimized supply chain, identified transportation constraints, and the material science in printable materials provides a comprehensive snapshot of the history of additive construction and the current obstacles decision-makers must account for in choosing the appropriate construction method.

History

Additive manufacturing (AM) is a rapidly growing, young field. The idea started with a machine that could 3D print an object rather than using ink like traditional computer printers for a 2D representation. The initial printers used nozzles to heat an element to its melting point and extrude the material layer-by-layer. Many companies took this idea and implemented the technique in system processes such as prototyping and modeling. This advancement created a boom in 3D printing dubbed the "Third Industrial Revolution" (Berman 2012).

Creating an object in 3D space primarily uses metals and plastics; however, individuals began exploring the use of these techniques with other materials. In 1995,

Behrokh Koshnevis applied the printing technique to concrete construction. He used a machine to manipulate cementitious materials, aggregate, and reinforcement additives to print large freeform structures. This construction technique's success eventually evolved to the term "additive construction" (Labonnote et al., 2016).

In the years since Koshnevis' successful use of additive construction, many countries have pushed the limits of possibility in additive construction. In Amsterdam, architects developed a unique 3D printer that was able to fabricate a canal house. The house was printed in segments and combined to produce a 12-room building (Wu et al., 2016). In Dubai, a Chinese company constructed an office building printed in Shanghai and shipped it to Dubai. The total printing and assembly time was 19 days, costing $140,000 for a 241.5 square meter building (Camacho et al., 2018). For this reason, Dubai expects 30% of its structures will be 3D printed by 2030 (Camacho et al., 2018). Additionally, in the United States, the National Aeronautics and Space Administration has provided research awards to develop AM technology for space construction. The intent is to use in-situ materials on the moon or Mars to build structures autonomously (Wu et al., 2016).

The continued success of additive construction captured the United States Army's attention. In 2015, the Engineer Research and Development Center Construction Engineer Research Laboratory (ERDC-CERL) established the Automated Construction of Expeditionary Structures (ACES) program. The goal of ACES is to provide custom-designed structures with minimal personnel, time, and materials (ACES, 2019). Since 2015, ACES has performed an analysis on the construction process, the printing speed, and the deployability of equipment compared to conventional construction methods

(Diggs-McGee et al., 2019; Kreiger et al., 2019; Kreiger et al., 2020). With the research's support, ERDC-CERL successfully demonstrated the capabilities in three different locations throughout the U.S. (Kreiger et al., 2020).

While the printing equipment is critical to additive construction's feasibility, the material composition determines the structural potential. The majority of studies focusing on the material composition demonstrate this importance. The extruded material must maintain its shape and not collapse under its weight or the layers above it (Papachristoforou et al., 2018; Al-Qutaifi et al., 2018). The literature considered various aggregates, binding materials, and additives to achieve the desired properties. For example, recycled materials reduce cost and shrinkage, while fiber additives increase strength (Bos et al., 2019; Papachristoforou et al., 2018; Thaarrini and Dhivya, 2016). The research in material development is extensive; however, the material research lacks incorporating the cost in implementing additive construction as a viable substitute to conventional construction.

Cost Comparison

When considering additive construction as an alternative to conventional methods, the seven key viability factors are structural design, process efficiency, environmental impact, logistics, labor, materials, and cost (Jagoda et al., 2020). There are significant investigations into the material science behind printing concrete structures; however, the research has overlooked the associated costs. The logistics and transportation, labor, and material considerations form a cost trifecta that needs to be

addressed. Each piece gives a better understanding of the costs of using additive manufacturing techniques over conventional construction methods.

Materials

Minimizing material costs while meeting demand is critical in the construction industry (Meng et al., 2018). According to studies by the Construction Industry Institute, material and equipment costs can be up to 60% of the total project cost (Meng et al., 2018). Additive construction techniques use 40% fewer materials than conventional construction, thereby showing potential cost savings using comparable materials (Allouzi et al., 2020).

One of the concerns with the material cost is relying on proprietary prepackaged materials for printing. These materials introduce difficulties in logistics, including availability and transportation (Kreiger et al., 2020). One solution would be to use locally accessible materials. The most common form of binding material used in concrete is Ordinary Portland Cement (OPC). What makes OPC so dominant is the availability of the natural resources needed and how easy it is to manufacture (Biernacki et al., 2017). The OPC, mixed with water and an aggregate, creates a chemical reaction that starts the hardening process (Camp, n.d.). Traditional construction methods use a significant amount of water to affect the strength properties of self-compacting concrete positively; however, this negatively affects the concrete's ability to maintain its layer shape and not collapse under its weight and the layers above it when printing (Al-Qutaifi et al., 2018; Hambach and Volkmer, 2017; Nematollahzade et al., 2020; Papachristoforou et al., 2018). When developing a binder material, a cost-saving goal should be to incorporate as much readily available material, like OPC, as possible.

One of the additional benefits of using OPC as a base material is its variety. Environmental conditions are primary considerations for the deployment of additive construction (Kreiger et al., 2020). Ten types of OPC are usable in different environments (American Society for Testing Materials, 2019). For example, low water-to-cement mixtures use air-entraining cement to improve workability, an essential requirement for additive construction material composition (Papachristoforou et al., 2018). Table 1 shows the different types of Ordinary Portland Cement.

Table 1. Types of Ordinary Portland Cement
(American Society for Testing Materials, 2019)

Type of Cement	**Usage**
Type I	No special properties
Type IA	Air entraining
Type II	Moderate sulfate resistance
Type II(MH)	Moderate heat of hydration, Moderate sulfate resistance
Type II(MH)A	Air entraining, moderate heat of hydration, moderate sulfate resistance
Type IIA	Air entraining, moderate sulfate resistance
Type III	Rapid setting, high early strength
Type IIIA	Air entraining, rapid setting
Type IV	Low heat of hydration
Type V	High sulfate resistance

Another factor to consider when using concrete for construction is the weather effect. Low temperatures, high winds, and precipitation can affect concrete placement productivity rates (Usukhbayar and Choi, 2018). Temperatures between 0°C and 40°C limit construction pouring activities, with any temperatures below this range degrading the concrete's final strength (Ballesteros-Pérez et al., 2015). On the other side, hot weather can cause an increase in evaporation in concrete. This effect alters the water-to-

cement ratio and reduces the compressive strength (Abbasi and Al-Tayyib, 1985). Higher temperatures and humidity levels increase cure rate in additive construction (Diggs-McGee et al., 2019). The environment can make layering difficult if the extruder adds a new layer before the next layer has had enough time to set or if the duration is too long and results in concrete curing before it is placed.

Additionally, the heat on the equipment may cause premature curing, thus leading to pumping and extruding problems. One of the most common delays in additive construction is the material curing too quickly (Diggs-McGee et al., 2019). Additives are mixed in the concrete to allow for lower temperature mixtures or reduce the water required to achieve optimal strength to combat weather effects (Al-Negheimish and Alhozaimy, 2008; Nmai, 1998).

Precipitation is another factor that affects concrete operations. El-Rayes and Moselhi (2001) found that paving operations were more susceptible to small amounts of rainfall than temperature changes. The added water decreases viscosity, thus making it more difficult for the concrete to hold form in additive construction (Ballesteros-Pérez et al., 2015). One of the most damaging delays in additive construction is the material being too fluid to properly maintain the shape (Diggs-McGee et al., 2019).

While OPC is typical because of its availability and cost, future environmental regulations may increase the cost globally. Many countries have implemented a tax on carbon dioxide emissions. After fossil fuels and land-use change, cement production is the third-largest producer of carbon dioxide emissions (Bellum et al., 2019). The amount of emissions generated by OPC production adds up to $64 per short ton produced (Biernacki et al., 2017). This cost leads to seeking recycled materials as a substitute for

OPC. The price to create a binder using recycled materials, such as geopolymers, is 11% cheaper than OPC (Thaarrini and Dhivya, 2016). These materials are equally abundant as OPC since the fly ash used in much of the recycled binders is a side-effect of consuming coal, the second most consumed fuel for energy generation.

Additionally, geopolymers do not utilize calcium carbonate; therefore, they produce fewer greenhouse gas emissions in the manufacturing process (Al-Qutaifi et al., 2018; Jeevanandan and Sreevidya, 2020). One of the main drawbacks of geopolymers is the increasing levels of corrosion in the materials. Typical Portland cement concrete establishes strength from the mixture of water and calcium silicate hydrates. This mixture creates strength through the reaction of dissolving alumina and silica oxides in a medium with high alkalinities, such as sodium hydroxide or sodium silicate (Gunasekara et al., 2019). While the reaction is promising for strength, the high alkalinity is a cause of concern because of the handling instructions required for the mixture. This concern is an advantage to additive construction compared to conventional construction when using geopolymers to reduce environmental impacts. If emission reduction in the construction industry comes to fruition, the minimal personnel required for additive construction will reduce health and safety risks (Demyanov and Popov, 2019). In total, additive construction can reduce labor and material costs, allowing AM to reach its cost-effective potential and reduce the environmental impacts (Ma et al., 2018).

Both OPC and geopolymers raise concerns about the buildability in additive construction. Proprietary printable mixes primarily consist of these cementitious materials along with a plasticizer, stabilizer, and shrinkage-reducing additives (Kreiger et al., 2020). These additives will enhance the development rate, reduce shrinkage and

deformation, and maximize the stiffness during the layer set time (Panda et al., 2019). Peat and fibers are two potential additives for OPC or geopolymers. Peat is an additive that increases the cement mix's strength during the initial 28-day strength phase (Demyanenko et al., 2018). Fiber infusion adds microfibers of carbon, glass, basalt, or other materials that provide tensile and flexural strength (Hambach and Volkmer, 2017). The use of geopolymers, in conjunction with fiber additives, has shown positive results (Al-Qutaifi et al., 2018).

Using proprietary prepackaged materials for printing significantly increases the costs due to increased transportation, logistics, and material costs (Kreiger et al., 2020). Incorporating these material costs increases the project cost; therefore, a more cost-effective material needs to be developed (Diggs-McGee et al., 2019). Designing a material that can primarily use locally sourced materials can reduce transportation costs by up to 80% (World Bank Group, 2009). Reducing these costs minimizes additive construction's life-cycle cost, thus making it more appealing as a viable and cost-efficient alternative to conventional construction.

Transportation and Logistics

The logistics viability factor is a set of activities to control the supply chain that generates value to the production by supplying, producing, and distributing a service or product (Díaz et al., 2015). The construction supply chain is a network of material suppliers, contractors, and owners. The chain works together to supply each piece of the network with benefits that working alone would not achieve (Yang and Lv, 2010). There is a need to maintain close coordination due to each network connection's importance (Hsu et al., 2019). A more complicated structure may require a more extensive network

when using conventional construction. Additive construction creates a smaller, sustainable chain. The shorter list of material requirements has a subsequent reduction in transportation requirements and reduces the supply chain (Ford and Despeisse, 2016). Supply chain reduction is critical to cost savings as it represents up to 30% of project expenses (Díaz et al., 2015). The material list includes the raw materials for the project and the parts and tools required for the maintenance of construction equipment.

The reduced maintenance and design adjustment costs are additional advantages to additive construction compared to traditional methods. As previously stated, adjustments to the design are quick and efficient. This advantage reduces the requirement for spare parts supply and storage. The process also eliminates the need for expensive retooling (Braziotis et al., 2019; Ford and Despeisse, 2016). Project demands like last-minute design changes are large contributors to schedule overruns that negatively impact the budget (El-Kholy, 2013). The supply chain needs to have a configuration to allow for minimal downtime by providing a surplus of spare parts to minimize the change costs seen in conventional construction. This supply chain demand comes with inherent adverse risks, uncertainty, and planning errors (Braziotis et al., 2019). Additive construction reconfigures the supply chains to be sustainable and simple by replacing multi-supplier scenarios with single raw components on-site and reducing storage requirements on bulky premade products (Braziotis et al., 2019; Ford and Despeisse, 2016). Additive construction gives a glimpse into a future where value chains are smaller and more sustainable because the materials are more sustainable and require fewer supply trips (Ford and Despeisse, 2016).

It is important to note that the total life-cycle cost of a project scales with the project. The life-cycle cost includes upfront, maintenance, and downtime costs. The upfront costs are higher with additive construction than conventional construction; however, the structure's size and complexity dilute the upfront cost (García de Soto et al., 2018). While additive construction is at a disadvantage in small production volumes, having lower maintenance and downtime costs on large-scale projects reduces overall costs (Westerweel et al., 2018).

Transportation is a crucial piece of logistics that maximizes the value of the project. Choosing the appropriate transportation distribution channel reduces costs and increases service levels (Díaz et al., 2015). Transportation modes provide speed, handling, and accessibility while acknowledging the risks and environmental impacts. Each of these transportation factors has cost tradeoffs. An increase in speed, handling, and accessibility is directly correlated to increased cost, while risk and environmental impacts are negatively correlated. There are economic principles that affect transport efficiency. The cargo size is negatively correlated to the cost, the distance is positively correlated to costs, and transportation scarcity is positively correlated to costs (Díaz et al., 2015). In remote locations, these principles are vital. Careful consideration of material requirements may have a considerable impact on the project's overall cost.

The raw material on hand is a large contributing factor to the lower maintenance and downtime costs. This cost is reduced by minimizing the storage requirements and reducing transportation requirements for the material (Ford and Despeisse, 2016). One area to highlight the advantages of additive over conventional construction is premade concrete structures and the associated material requirements. The occupied volume of

premade structures increases demands on storage and transportation requirements (Braziotis et al., 2019; Ford and Despeisse, 2016). For example, vehicles have limitations on cargo volume. Additive manufacturing has a reduced footprint because only raw materials are transported compactly (Díaz et al., 2015). According to the National Precast Concrete Association, a standard traffic barrier is 3' x 2' x 12' (which represents a volume of 2.04 cubic meters). However, the equivalent raw material occupies 0.85 cubic meters, a 59% reduction ("Precast Concrete Traffic Barriers," 2014). The raw material is also more versatile for construction. All concrete structures made on-site using the same raw materials reduce inventory holding and obsolescence costs of various premade structures (Braziotis et al., 2019).

Conventional and additive construction both have equipment costs; however, unlike additive construction, conventional sites may obtain equipment from local sources. This requirement is an upfront cost of additive construction diluted by the cost savings from the lower material and construction costs (García de Soto et al., 2018). Estimates must consider air transportation costs to import equipment to remote sites.

According to the World Bank Group (2009), air freight cost is 4-5 times the cost of ground transportation. The largest expenditure for air freight transportation is the fuel cost. Though the efficiencies have changed over the years, 28.2% of total operating costs for airlines came from fuel costs in 2019, as opposed to 15%-25% between 1993 and 2008 (Khan et al., 2019; Miyoshi and Fukui, 2018). This high cost has led to a focus on controlling excess fuel consumption. Loading suboptimal fuel for the trip may result in using reserve fuel tanks, whereas loading too much fuel may increase ramp weight and limit the amount of cargo allowable. Additional loaded fuel affects engine performance

and can cause extra wear and tear on the engine, as well as cause excessive fuel consumption. A ratiometric expresses the fuel efficiency for aircraft, which measures the amount of fuel per unit of measure. For construction transportation, the unit is usually per ton-mile (Khan et al., 2019). Material transportation accounts for a substantial portion of both project cost and time, further highlighting its importance (Xu and Gang, 2013). Additive construction material needs to incorporate locally sourced material to reduce the amount of material transported via air.

The construction design needs to consider the printer type, materials, material delivery, transportation, and environmental conditions (Kreiger et al., 2020). Today, 3D printing of structures mostly uses a pumping technique to pump paste, mortar, or concrete in layers (Lin et al., 2018). The additive construction equipment must have the ability to manipulate cementitious materials, aggregate, and reinforcement additives to print large freeform structures (Al-Qutaifi et al., 2018). As previously stated, the concrete extruded from the printer must maintain its shape and not collapse under its weight or the layers above it (Al-Qutaifi et al., 2018; Papachristoforou et al., 2018). Research in 2016 on vertical stresses concluded the rest time between the layers needs to be calculated for each type of material to optimize vertical strength (Perrot et al., 2016). The primary way to achieve the correct buildability is to evaluate the various components of concrete.

Labor

Additive construction has the potential to solve this problem of low construction productivity. The advantages of using additive construction compared to traditional construction include less waste, freedom of design, faster construction times, fewer labor costs, and reduced safety risks on sites (Abdulla Al-Safy, 2019). These advantages have

a direct correlation to the cost of the project. Minimizing waste, time, and labor costs positively benefit a construction project.

Most of the benefits that come from additive construction are associated with labor costs. Labor costs are around 50% of the total project cost, with cast-in-place construction's formwork accounting for up to 60% of the construction labor cost (Diggs-McGee et al., 2019; Kreiger et al., 2019). The previously mentioned additive construction project in Dubai, with a $140,000 price tag, had a savings of 70% on labor costs.

The construction industry is one of the most vulnerable to extreme weather conditions due to its heavy reliance on labor and outdoor activities (Alshebani & Wedawatta, 2014). Since the superstructure is the exterior of the building, the weather is an external factor in construction. Additive construction is considered a potentially viable alternative for the superstructure of a building. Weather factors may cause unpredictable effects, including increased costs and delays (Alshebani & Wedawatta, 2014). Research finds that weather factors tend to decrease worker productivity. These factors include temperature, humidity, precipitation, and wind (Acharya et al., 2018; Moohialdin et al., 2019; Kjellstrom et al., 2009; Ghani et al., 2020; Budhathoki and Zander, 2019; Koehn 1985). These factors affect both conventional construction workers and additive construction workers alike.

Temperature and humidity variations are negatively correlated to worker productivity and can cause productivity variation of up to 64% (Moohialdin et al., 2019). Prolonged exposure to heat has adverse effects on the body. Studies have found that for each 1°C increase in the temperature, worker productivity decreased by up to 57% from

the previous level (Li et al., 2016; Moohialdin et al., 2019). The productivity decrease is also exponential as the temperature increases. For example, if at 23°C a worker can produce 100 units, and a 1°C increase results in 95 units built, the outcome is a 5% decrease. If the temperature increased by another 1°C and the worker produced only 90 units, the result is a 5.3% decrease from the previous temperature increase and a 10% increase overall. This scenario is assuming the worker performed direct work for the entire hour. Li et al. (2016) found direct work time decreased by 0.57%, and idle time increased by 0.74% during that same temperature change. This fact means the worker is taking longer breaks over the day. Though the percentage seems low, it equates to three minutes lost per eight-hour day per 1°C increase. The accelerated rate of climate change expects that hot weather will be more impactful to worker productivity (Al Refaie et al., 2020). For example, India expects to show a loss of work capacity of 8% with a 2.7 °C temperature change (Kjellstrom et al., 2018).

The increased temperature also produces other effects outside of direct work. These effects are psychological limits caused by the stress of being in hotter environments (Orlov et al., 2020). The increased heat effects lead to slower work, more mistakes, and an increased risk of accidents on the job site (Kjellstrom et al., 2018). High temperatures do not affect additive construction printers to the same extent. Using printers would minimize the risk of heat-related injuries, including heat rash, heat cramps, heat exhaustion, and heat stroke (Moohialdin et al., 2019).

Precipitation is another weather factor significantly affecting worker productivity. The lightest rain can reduce labor productivity by up to 40% (Larsson and Rudberg, 2019). This reduction is primarily due to workers spending time to protect the worksite

and set up mitigation measures during the initial rain event (Larsson and Rudberg, 2019). Continuous rain events that span multiple days progressively decrease productivity (Guo, 2000).

These continuous precipitation events often become extreme weather events such as hurricanes, thunderstorms, and, when below freezing, blizzards (Alshebani and Wedawatta, 2014). These extreme weather events cause increased precipitation and wind. Strong winds have damaging safety effects on construction operations (Larsson and Rudberg, 2019). Formwork is highly susceptible to high winds, reducing productivity by up to 25% (Larsson and Rudberg, 2019). Formwork is not utilized with additive construction, thus creating a potential advantage over conventional construction, dependent on the wind limitations of additive construction, in windy environments.

Temperatures below freezing also have adverse effects on worker productivity. Studies show that productivity drops by up to 50% during cold weather events (Larsson and Rudberg, 2019; Thomas et al., 1999). The effect of a cold-weather event, such as snow, expands past the days of the event due to frost, snow build-up, and high winds following storms (Thomas et al., 1999). The productivity decrease for cold weather days manifests itself through material deliveries, fabrication errors, and equipment relocation (Thomas et al., 1999).

One way to reduce weather labor risk is by minimizing the amount of personnel required to operate construction machinery. Human interaction on an additive construction site is only needed for installation, maintenance, and performance observation of the equipment (Demyanov and Popov, 2019). For example, the office buildings printed in China and Dubai only used one monitor for the entire printing

process (Al-Safy, 2019). Printers also outlast the personnel required to monitor equipment use. Printers can continuously print for 12-24 hours (Diggs-McGee et al., 2019). The speed at which printers can complete activities reduces construction time by up to 30% and lowers labor costs by up to 80% (Al-Safy, 2019).

Another piece of the human factor in construction is the complexity and task feasibility. With conventional construction, worker productivity decreases as work complexity increases. This productivity directly ties to costs per square meter (García de Soto et al., 2018). This connection is not the case for additive construction. If the complexity and size of the project increase, the cost per square meter stays relatively constant. This consistency allows for an increase in flexibility and design freedom without the additional expenses (Al-Safy, 2019; García de Soto et al., 2018). Additionally, additive construction gives designers and engineers the ability to adapt to unique environments without the concern of going over budgetary constraints (Demyanov and Popov, 2019).

Quality of work is an additional concern that could be reduced with the implementation of additive construction. High temperatures, humidity, and precipitation all negatively affect construction quality and increase personal safety risk (Li et al., 2016; Moohialdin et al., 2019). Additive construction printers utilize computer software that instructs the machine to direct movement to precise locations. Additionally, the software allows for rapid adjustments in the parameters to account for variability in the environment (Kreiger et al., 2020).

Decision-Making Models

Decision-making is the process of choosing actions according to desires and beliefs (Nady and Li, 2020). The action is to perform a process that should lead to expected results (Li et al., 2020). The process that leads to the decision stems from one of many decision-making models. The choice to provide a decision-making model in this research opens the door to numerous model opportunities. The models range in complexity from the classic decision-making model and the Markov decision processes to Fuzzy Logic models that remove the binary decision choices. While each model has its merits, not every model would be applicable for this research. The decision models examined are Bayesian Networks, Prospect Theory, Evolutionary Game Model, Naturalistic Decision-Making Theory, Prescriptive Analytical Decision-Making, Schemata and Mental Model, and Recognition-Primed Decision Making.

The first model under consideration is the Bayesian Network model. This model uses networks of nodes and edges to provide a web of knowledge-linking information. Graph theory uses weights and directs connections in the network to focus on probabilities and uncertainties to make decisions (Shi et al., 2020). This method does not apply to construction comparison since the two approaches are not directly related to each other, and graph theory cannot capture the uncertainties.

The next models under consideration are Prospect Theory and Evolutionary Game Model. Prospect theory is used for decision-making when people are facing risk. This theory has exceptional value when describing how players will act under known risk (Liu et al., 2020). This model can be amplified into Evolutionary Game Model by incorporating multiple players. Evolutionary Game Model puts multiple players into a

scenario and sets known risks to each member. Each player's decisions directly impact the others, thus causing a reaction from that decision and the predetermined risk (Liu et al., 2020). While the comparison of additive and conventional construction is a multiple-player scenario, one's building decision does not affect the other; therefore, these models do not apply to this research (Liu et al., 2020).

Instead of analyzing the two construction methods in direct competition with themselves, a naturalistic approach of looking at each method individually may be optimal. The Naturalistic Decision Model, Prescriptive Analytical Decision-Making Model, and Schemata and Mental Model all focus on how decision-makers gather information to make decisions (Li et al., 2020). Developed in 1989, the Naturalistic Decision Model examines how decision-makers choose an action while incorporating consequences, both personally and organizationally. This model relies on eight factors: ill-structured problems, uncertain environments, poorly defined goals, action and feedback loops, time stress, high stakes, multiple players, and organizational goals (Li et al., 2020). Prescriptive Analytical Decision-Making takes these factors and states that people will collect all relevant information to make the best decision. Li et al. (2020) further combine the Naturalistic Decision Model with the Schemata and Mental Model to allow experts to make quick decisions. The logic behind this model is that experts have more experience and a better understanding of relevant information; therefore, they can make better decisions (Li et al., 2020). These models are great for decision-makers who are knowledgeable in their respective fields and can choose relevant information while identifying incorrect information quickly. Since additive construction is a newer method

though, the field experts are not likely to be the decision-makers for the optimal construction method.

The final models under consideration are the Recognition-Primed Decision-Making Models. These classical models lead to choosing an action based on the reasoning process from pattern recognition and experience to reach decisions without outside effects in realistic environments (Nady and Li, 2020). The classical decision-making model will gather information to present to decision-makers with simplicity to garner a quick response with relevant information. In this research, the relevant information presents decision-makers with a clear picture of which construction method is more cost-effective.

Summary

The literature shows that additive construction exhibits significant construction impacts regarding labor, logistics, transportation, and material costs. The variability in these factors creates uncertainty that needs addressing. Combining these cost factors will guide decision-makers to which option has a more optimal cost-benefit. The labor costs are significantly affected by task feasibility from complexity and weather. An increase in complexity will increase the cost per square meter of a structure in conventional construction. The weather can significantly reduce worker productivity, thereby increasing required labor hours and extending project durations. Both factors will increase the overall project costs.

Additive construction significantly reduces logistics and operations costs due to the decreased supply chain. The project with additive construction requires less material

and equipment in both quantity and variation. This decrease will reduce the number of suppliers, shipments, and repairs on equipment. The reduced shipments apply to both ground and air transportation. The transportation decision must consider the weight and the volume capacity of a vehicle. Conventional construction that relies on the delivery of premade structures incurs additional transportation costs per unit volume.

While conventional construction may have increased labor, logistics, and transportation costs, the material cost can make additive construction more expensive. The use of proprietary materials instead of local materials will result in more considerable material costs and require a more costly transportation network to supply the job site. Analyzing each of these factors will give decision-makers a better understanding of the costs associated with each construction method.

III. Methodology

The purpose of this chapter is to provide a replicable procedure to the research and produced results. First, the literature review identified the variables of materials, logistics and transportation, and labor as being critical for the decision-making model. Second, data for each variable is gathered from Air Force Instruction documents, industry-accepted cost estimating software, commercial cost documents, and historical data from past projects. Next, both construction methods are analyzed independently to obtain total project costs. Comparing these costs determines the most cost-effective method for each scenario. Lastly, a sensitivity analysis is performed on the air distance to identify an air freight distance that would shift the cost-effective choice from one method to another.

Identification of Variables

The literature review identified materials, logistics and transportation, and labor costs as critical variable categories in project cost. The material costs include the material and the equipment. The transportation requirements consider the volumetric and mass limitations to accompany the fuel costs. The labor costs account for hourly requirements and the respective fee per hour based on the task. This model is intended to be used for both commercial and military application; however, the collaborative work has been with ERDC-CERL. Therefore, the variable identification and application is focused around military application.

Materials

The materials required for additive construction need to be extruded from the printer while maintaining the layer shape and not collapsing under its weight or the layers above it. The raw materials are cementitious materials, aggregate, and water. The U.S. Army Engineer Research and Development Center Construction Engineer Research Laboratory (ERDC-CERL) has researched various material compositions to best suit the additive construction printer (Rushing et al., 2019). The cost of the mixture breaks down into two categories: locally sourced and imported. Markets nearby the construction site supply the locally sourced material (M_{LS}). Ground transportation delivers this material. The imported material (M_{Im}) is not found locally and must be purchased at a distant location and brought to the local area. The total material cost (M) also includes the construction equipment delivered to the project site. The equipment cost is considered the upfront cost. Separating the two types of materials aids in determining logistical expenses discussed in the next section. Equation 1 calculates the total cost by combining all material costs in U.S. Dollars.

$$M = M_{LS} + M_{Im} \tag{1}$$

Conventional construction materials follow the same process. The cost and volume of materials differ from additive construction and need to be processed separately. Conventional construction may require additional vehicles not used for transportation. The construction project's material cost includes these vehicles. RS Means provided the project's material and vehicle costs ("RSMeans Data," 2020.). Additionally, the RS Means software included labor hour requirements with location factors contained.

The case study material and equipment quantities for additive construction originated from research conducted by ERDC-CERL. The quantities for the conventional construction equivalent used RS Means data. The additive construction data is actual cost data from the projects, while the conventional construction data is an estimation based on what would be needed to create a comparable structure.

Logistics and Transportation

Transportation of the materials and equipment is a critical logistical cost to consider. The distances provided by ERDC-CERL between the project sites found in the case studies and both the local source and the source airport from which materials originate from via air freight add substantial cost. The volume and weight of the material and equipment transported dictate the vehicle type and the number of selected vehicles. The case studies show a list of material and equipment requirements. This process is the same for both air and ground transportation. The vehicles used for this research are from U.S. Air Force inventories and standard global ground vehicle companies.

The aircraft information used by the Air Force came from Air Force Instruction (AFI) 65-503. This document provides fuel factors used for the aircraft as a cost per flight hour (F_A). The distance is divided by the cruising speed to get the flight time and air cost for using a specified aircraft. That time is multiplied by the cost per flight hour to determine the overall cost of the flight. The cost per flight hour incorporates fuel factors, supplies, maintenance, and equipment costs. Each aircraft has different weight and volume capacities. Palletized material and equipment optimize space. The Air Force uses 463L master pallets for cargo loads. The dimensions of the 463L are 2.13 meters by 2.64 meters of usable space. According to the Air Deployment Planning Guide, GTA55-

07-003, the height restriction is 2.44 meters, thus bringing the total allowable volume to 13.73 cubic meters per pallet ("FM 55-9 Appendix D," n.d.). Table 2 shows two typical Air Force aircraft with their weight and volume capacities, cost per flight hour, and cruising speeds. These factors will provide an overall cost for air transportation.

Table 2. Aircraft Data

Aircraft	**Max Volume (V_A)**	**Max Weight (W_A)**	**Cost Per Flight Hour**	**Cruising Speed**
C-130J	6 pallets	25,000 lbs	$5,776	644 KPH
C-17A	18 pallets	135,000 lbs	$12,923	837 KPH

Note: Data obtained from AFI 65-503: U.S. Air Force Cost and Planning (2018), C-130 Hercules (n.d.), C-17 Globemaster III (n.d.), and FM 55-9 Appendix D (n.d.)

PLS Logistics Services (2015), a commercial company, provided the ground vehicle information. The fuel efficiencies for ground vehicles vary; however, studies in freight vehicle fuel efficiency showed an average between two to three kilometers per liter (Marsh, 2015). Table 3 shows sample volume capacities for three trucks.

Table 3. Ground Transportation (PLS Logistics, 2015)

Vehicle	**Max Volume (V_G)**	**Max Weight (W_G)**
Flatbed	98.2 cubic meter	48,000 lbs
Step Deck	111.6 cubic meter	48,000 lbs
Double Drop Deck	122.4 cubic meter	45,000 lbs

The next pieces to consider with vehicle transportation are the weights and volumes of the materials and equipment listed for each construction method using unit weights or information from ERDC-CERL. The weight of raw materials consists of the

unit material weight (W_M) multiplied by the number of units (N_M). This number is compared to the maximum weight allowed per vehicle by either air (W_A) or by ground (W_G). The material volumes followed the same format with the unit material volume (V_M) multiplied by the number of units (N_M), which was then compared to the maximum volume per vehicle by either air (V_A) or by ground (V_G). The volume and weight of the equipment are only for equipment requiring an external vehicle. Volume and weight requirements did not include vehicle equipment driven to the site. The total weight and volume determine the number of vehicles and volume. Equation 2 is the equation for the number of vehicles required based on the material mass and volume. The number of vehicles (N_V) is the maximum between the number of vehicles based on mass (N_{V1}) and the number of vehicles based on volume (N_{V2}).

$$N_{V1} = \frac{\sum W_M \times N_M}{(W_{A\ or\ G})} \tag{2}$$

$$N_{V2} = \frac{\sum V_M \times N_M}{(V_{A\ or\ G})} \tag{3}$$

$$N_V = max(N_{V1}, N_{V2}) \tag{4}$$

Both ground and air transportation use Equations 2-4. The resultant variable stems from the vehicle type analyzed, the number of aircraft (N_{VA}), and ground vehicles (N_{VG}). The number of vehicles is combined with the fuel efficiency and distance to determine the transportation cost associated with the project. The total transportation (T) cost, in dollars, is found from Equation 5. The air freight cost consists of the number of air vehicles, calculated from Equation 4, multiplied by the air-fuel cost per hour (F_A) and the distance traveled by air (d_A), and divided by the cruising speed in kilometers per hour (S_{Cr}). The ground vehicle portion includes multiplying ground fuel cost per liter (F_G) and

the distance traveled by ground (d_G), and divided by the efficiency in kilometers per liter (KPL). This number adds to the upfront usage cost of the vehicle (C_{VG}). The combination of these two parts multiplies by the number of ground vehicles, also calculated from Equation 2. The air and ground pieces of the ground transportation add together to get the total transportation cost in U.S. Dollars.

$$T = \frac{N_{VA} \times F_A \times d_A}{S_{Cr}} + (N_{VG})(\frac{F_G \times d_G}{KPL} + C_{VG}) \quad (5)$$

The cruising speed and cost per flight hour originated from U.S. Air Force fact sheets and Air Force Instructions **(**"AFI 65-503: U.S. Air Force Cost and Planning," 2018; "C-130 Hercules," n.d.; and "C-17 Globemaster III," n.d.). The national averages for the vehicles and diesel fuel costs determine the KPL and fuel costs (PLS Logistics, 2015). Both additive and conventional construction use the total transportation cost equation. If a project site does not contain an airfield, vehicle transportation is added from the airport to the project site using the same calculations.

Labor

The final variable category to be considered is labor. The labor costs for construction comprise upwards of 60% of total construction costs. The military does not concern itself with labor hour costs; however, for a true cost estimate, labor hours are attached. The prices shown are strictly labor costs and do not incorporate the expenses associated with health risks and workplace accidents that may take place on construction sites. The labor calculation begins with the number of labor hours per activity (H_{Ac}) required to perform the construction project as listed in each case study's activity breakdown. The labor hour number is multiplied by the cost to perform each action. RS Means provided the labor hours required to complete a construction activity and the

associated costs (C_{AC}). The U.S. Army EDRC-CERL provided the labor hours and costs associated with monitoring the additive construction equipment. The total labor cost (L), found from Equation 6, is the summation of all labor activities with their respective time and cost in U.S. Dollars.

$$L = \sum H_{Ac} \times C_{Ac} \tag{6}$$

Comparison

Combining all of the cost calculations creates a final cost estimate. The individual cost factors for each method are independent of each other, and the final cost is the only cost factor compared. Equation 7 determines the total cost.

$$Cost\ of\ Construction\ Method = M + T + L \tag{7}$$

The cost of conventional construction is compared to the cost of additive construction for similar construction requirements. Decision-makers may use this cost estimate comparison for the optimal solution for the construction project. In Chapter IV, two real-world case studies compare two construction methods from previously completed projects. These comparisons illustrate the functionality of the decision-making model. An additional hypothetical case study adds a fictitious location and scenario. Through the method's steps, the decision is made to choose the aircraft and ground transportation to deliver the material to the project site. Afterward, the comparison of each method's total cost determines which method is ideal for the scenario.

Sensitivity Analysis

The total construction cost relies on the total distance from the local source and the flight path starting point to the construction site. A sensitivity analysis on the distance shows the optimal distance where one method surpasses the other as the optimal construction choice. The results and analysis section demonstrates the comparison between the two methods with and without a sensitivity analysis.

The breakeven point is calculated by equating Equations 8 and 9. The cost factors for the material and labor are held constant to the computed values in each case study. The variable examined is the air distance (d_A). The breakeven point is the distance where the cost of additive construction (C_{Ac}) equals the cost of conventional construction (C_{Con}).

$$C_{AC} = M_{AC} + L_{AC} + \frac{N_{VA1} \times F_{A1} \times d_A}{S_{Cr1}} + (N_{VG1})(\frac{F_{G1} \times d_{G1}}{KPL_1} + C_{VG1}) \quad (8)$$

$$C_{Con} = M_{Con} + L_{Con} + \frac{N_{VA2} \times F_{A2} \times d_A}{S_{Cr2}} + (N_{VG2})(\frac{F_{G2} \times d_{G2}}{KPL_2} + C_{VG2}) \quad (9)$$

It should be noted that the cost per flight hour (F_A) can exceed $5,000. With small projects, any costs savings for either method quickly diminish by a multiple hour flight. The sensitivity analysis shows at what distance the construction method choice changes due to the overwhelming air freight cost.

IV. Analysis and Results

This chapter utilizes the equations developed in the methodology to apply them to various case study examples. In the following case studies, the material is categorized as locally sourced or imported to obtain the material costs and choose the proper vehicle. The built structure determines the labor hours required to complete the project. The final price consolidates the material, logistical, and labor costs for each construction method within the case study. The optimal construction choice is based on comparing each construction method. A sensitivity analysis on the air freight distance shows at which point one method becomes more advantageous. The following case studies use information provided by U.S. Army Engineer Research and Development Center Construction Engineer Research Laboratory (ERDC-CERL) and RS Means for labor hour and cost requirements. The vehicles selected are for testing only and do not reflect actual scenarios.

Results of Simulation Scenarios

There were two structures printed by ACES using additive construction to compare to conventional methods. The first case study is a 47.6 square meter structure built at the ACES site in Champaign, Illinois. The second case study is a 10.1-meter bridge built at Camp Pendleton in California. These two case studies compare construction activity costs and durations. Each variable category entered a sensitivity analysis to determine the effects of distance on the overall costs. The discussion creates a fictitious scenario in a remote location. This case study demonstrates the capability of

the decision-making model to determine the optimal construction method. The appendix contains consolidated result tables.

Case Study 1

The first example of additive construction is the 47.6 square meter structure built by ACES in 2017. This structure demonstrates the ability to print a barracks for the army in an expeditionary situation. The printer produced the walls, while the foundation and roof relied on conventional construction methods. For this reason, this thesis compared only the walls in the construction cost analysis. Since the construction took place at the additive construction equipment home, a sensitivity analysis shows a breakeven distance point in cost. Before and after such a moment, one construction method has a cost advantage over the other. Figure 1 shows the finished product.

Figure 1. Finished 47.6 Square Meter Structure

The materials for the project are 100% locally sourced material, so M_{Im} is zero. The materials required for additive construction are concrete and reinforcement material. Since ERDC owns the equipment, there is no cost associated with the print. Table 4 shows the quantities of the material and equipment. The unit volume is eight bags per cubic meter, and the unit weight for concrete is 94 lbs per bag. The total material cost (M_1) is $5,960.51.

Table 4. Case Study 1 Additive Material

Item	Qty	Unit Volume	Unit Weight	Unit Cost	Total Volume	Total Weight	Total Cost
Concrete	500	0.125	94	$10.00	62.5	47,000	$5,000.00
Reinforcement Material	857.6	0.25	1	$1.12	214.4	857.6	$960.51
						M_1	**$5,960.51**

As previously stated, all material is locally sourced; therefore, there is no need for air transportation. The printing equipment is already on-site and will not be included in obtaining the vehicle number requirement. The volume and weight requirements are 211.7 cubic meters and 47,857.6 lbs, respectively. The smallest ground vehicle found in Table 3 fulfills the requirement with only one flatbed truck (N_{VG}). The distance to the local material source is 32.2 kilometers (d_G). The fuel efficiency of the flatbed truck is 3 kilometers per liter (KPL). The average fuel cost in Champaign, Illinois, is $0.74 per liter ($F_G$) as of 12 Jan 2021 (“AAA Gas Prices” n.d.). The daily usage costs for renting the flatbed trucks in Champaign is $453.27 (“RSMeans Data”, 2020). By placing these variables in Equation 5, a total transportation cost (T_1) is $500.93.

The printing operation took 16.75 hours to complete, based on current capabilities. The total estimated cost for operations and maintenance on the equipment is $75 per hour (Kreiger et al., 2019). Table 5 shows the activity breakdown from the print by activity and the cost of said activity. Each activity cost is the hours (H_{Ac}) required multiplied by the unit rate (C_{Ac}). The cost variables M_1, T_1, and L_1 are input into Equation 7. Adding these variables together results in a total cost of construction using additive construction equal to $7,717.69.

Table 5. Case Study 1 Additive Labor

Activity	Hours	Unit Rate	Total Cost
Operations and Maintenance	16.75	$ 75.00	$ 1,256.25
		L_1	**$ 1,256.25**

As seen with additive construction, the materials for conventional construction are 100% locally sourced and, therefore, M_{Im} is zero. The equipment needed for pouring concrete is assumed to be owned by ERDC. Table 6 shows the material required to create a concrete wall. The unit volume and weight of concrete are equal to the concrete used in additive construction. Kreiger et al. (2019) provided the formwork, support materials, and reinforcement materials information. The information stated the project used 13.61 cubic meters of concrete. A bag of concrete is 0.02 cubic meter. These numbers result in a count of 801 bags of concrete to fill this requirement. The total material cost (M_2) is $9,757.47.

Table 6. Case Study 1 Conventional Material

Item	Qty	Unit Volume	Unit Weight	Unit Cost	Total Volume	Total Weight	Total Cost
Concrete	801	0.125	94	$10.00	100.125	75294	$8,010.00
Formwork	1512	0.0093	1.5	$0.33	14.0616	2268	$498.96
Form Support Material and Supplies	1440	0.0093	1	$0.20	13.392	1440	$288.00
Reinforcement Material	857.6	0.007	1	$1.12	6.0032	857.6	$960.51
						M_2	**$ 9,757.47**

The transportation requirement for conventional construction is ground vehicles. The volume and weight requirements are 5,808 cubic meters and 79,859.6 lbs, respectively. With these requirements, the optimal solution is to use two-step deck trucks. Going the same distance as additive construction with the same fuel costs puts the total transportation cost (T_2) at $333.95. The labor activities required for conventional construction differ from additive construction. The activity breakdown in Table 7 shows a large amount of time devoted to formwork. The other activities make up a fraction of the cost. In all, the total labor cost (L_2) is $5,227.80. Again, combining the variables M_2, T_2, and L_2 in Equation 7 gives a total construction cost of $15,319.22. This results in a conventional construction cost 50% higher than additive construction.

Table 7. Case Study 1 Conventional Labor

Activity	Hours	Unit Rate	Total Cost
Form Work	173.2	$21.50	$ 3,723.80
Concrete Pour	16	$35.00	$ 560.00
Reinforcement	32	$29.50	$ 944.00
		L_2	**$ 5,227.80**

In remote locations, the printing equipment will need to be flown to the project site. The transportation cost increased significantly for every hour flown. A sensitivity analysis using an HC-130J, a standard Air Force cargo aircraft, determines at what distance conventional construction becomes more profitable. The variables accounted for are the cruising speed (S_{Cr}) and cost per flight hour (F_A), as seen in Equation 5. The cost of labor, materials, and ground transportation all stay constant. The only piece moved from locally sourced material to imported is the printing equipment. Using Equation 8, the variable in question is the air distance (d_A). Figure 2 shows the results of the sensitivity analysis. Additive construction was cost-effective until the breakeven point of 847.5 kilometers was reached.

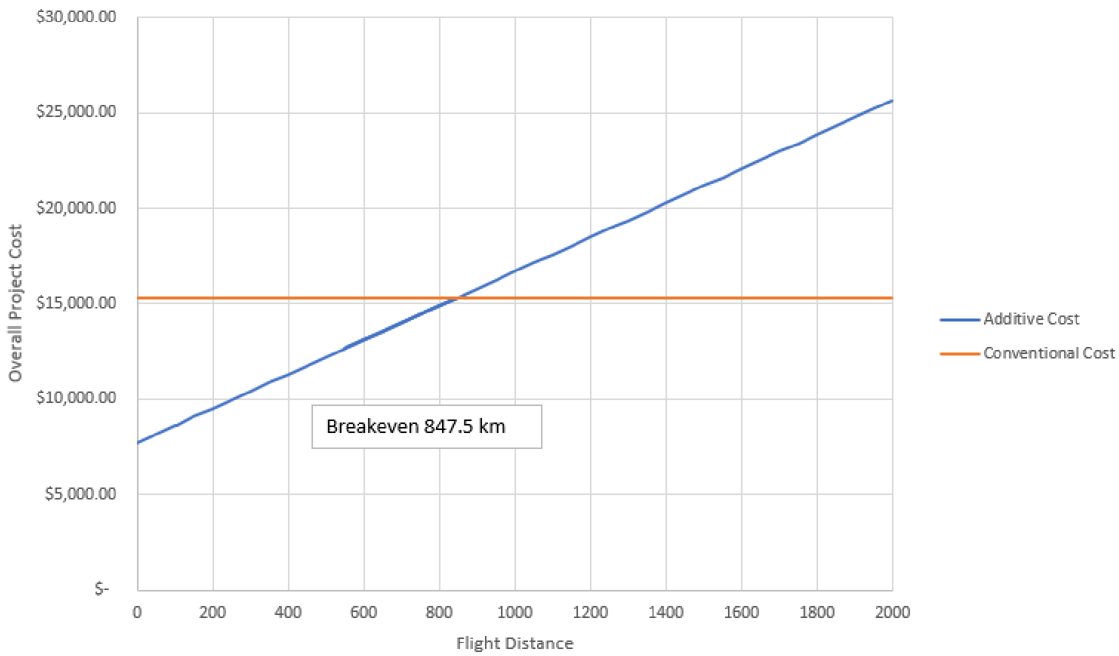

Figure 2. Case Study 1 Breakeven Analysis

Alternative Inputs

The case study focuses on Champaign being the home of the equipment for a 47.6 square meter structure. Additional analysis inspected whether this project would have been as efficient if it were constructed in an alternate location. This research chose Seattle, Washington, as the alternate location. The cost of the concrete and reinforcing materials were roughly the same, thus resulting in no change in the material cost for both additive and conventional construction. The distance to the project site was the same and resulted in no change in transportation costs. The labor costs were the same because of using the same personnel. This results in no change in the cost savings using additive construction for a 47.6 square meter structure.

The breakeven point for the 47.6 square meter structure is a 847.5-kilometer radius around the equipment origin. This drove the inquiry to investigate the effect on this radius if more than one structure was being constructed. With two structures of the same size, the breakeven point is 1,835.1 kilometers. Constructing five structures of the same size (238 square meters total) puts the breakeven point at 4,779.3 kilometers. This shows that the economy of scale will increase the cost savings to allow for a further distance in flying the equipment. Figure 3 shows the breakeven distances for one (black), two (blue), and five (red) 47.6 square meter structures. The figure is centered around Champaign, Illinois, but as previously stated, the center can be placed around any equipment staging point.

Figure 3. Project Size Breakeven Point

Case Study 2

Case study 2 gathers data from an exercise conducted at Camp Pendleton, California, in December 2018. In collaboration with ERDC-CERL and the United States Marine Corp, the exercise printed a bridge spanning 10.1 meters with two support piers. This bridge was the first printed bridge in the United States and was the world's first bridge printed in a field environment (Kreiger et al., 2020). RS Means cost estimating software estimated the conventional construction bridge using inputs to build a similar structure. Figure 4 shows the finished bridge.

Figure 4. Finished Printed Bridge

The materials for the project were sourced locally. ERDC-CERL flew the equipment in from Champaign, Illinois. As with Case Study 1, the equipment's upfront cost is zero because the equipment is already owned and operated by the ACES lab. The team purchased 240 bags of cement and 40 tons of aggregate with a unit volume of 0.59 cubic meters per ton. Table 8 shows the material quantities. The total cost for the material (M_3) is $6,400.

Table 8. Case Study 2 Additive Material

Item	**Qty**	**Unit Volume**	**Unit Weight**	**Unit Cost**	**Total Volume**	**Total Weight**	**Total Cost**
Concrete	240	0.125	94	$10.00	30	22560	$2,400.00
Aggregate	40	20.8	2000	$100.00	832	80000	$4,000.00
						M_3	**$6,400.00**

The transportation cost for additive construction breaks into two pieces: air and ground. The equipment was flown from the ACES lab to Camp Pendleton on an HC-130J. The distance between these locations is roughly 3,058 kilometers. The material was sourced from 32.2 kilometers away using three flatbed trucks to deliver the material

at a usage rate of $167.28 per truck and a fuel cost of $3.487. Using Equation 5 resulted in a total Transportation (T_3) cost of $27,920.92.

The labor costs are similar to Case Study 1 in that they both require three personnel to complete the task. The project took three days to finish, with the three operators working in unison. The activity breakdown in Table 9 shows the total labor cost (L_3) to be $6,840. The cost variables M_3, T_3, and L_3 are input into Equation 7. Adding these variables together results in a total cost for additive construction of $29,391.32. The transportation cost made up 60% of the overall cost.

Table 9. Case Study 2 Additive Labor

Activity	Hours	Unit Rate	Total Cost
Operations and Maintenance	72	$75.00	$5,400.00
		L_3	**$ 5,400.00**

Conventional construction of the same structure also uses all locally sourced materials. One key difference in using this construction method is the need for a concrete truck at this location. The cost of the truck was $1,000 per trip plus the cost of materials. The material quantities found in Table 10 show a total material cost (M_4) of $10,920.

Table 10. Case Study 2 Conventional Material

Item	Qty	Unit Volume	Unit Weight	Unit Cost	Total Volume	Total Weight	Total Cost
Concrete	600	8	94	$10.00	4800	56400	$6,000.00
Forms	600	1	1.5	$3.20	600	900	$1,920.00
Concrete Truck	3	0	0	1,000.00	0	0	$3,000.00
						M_4	**$10,920.00**

Since a concrete truck delivers the concrete, the concrete delivery's logistical cost is absorbed by the unit cost of the concrete truck. The delivered material is the formwork. This delivery requires one flatbed truck. With the average fuel cost in San Diego at $3.487 and the $167.28 usage rate, the total transportation cost (T_4) is $177.24.

The labor requirements for constructing a similar style bridge comes down to the activity breakdown in Table 11. This breakdown shows formwork comprising a large portion of the labor cost. The total labor cost (L_4) to create a similar bridge structure is $7,833.60.

Table 11. Case Study 2 Conventional Labor

Activity	**Hours**	**Unit Rate**	**Total Cost**
Form Work	106.8	$40.00	$4,272.00
Concrete Pour	118.72	$30.00	$3,561.60
		L_4	**$ 7,833.60**

The cost variables M_4, T_4, and L_4 are input into Equation 7. Adding these variables together results in a total cost of construction using conventional techniques to be $18,930.84. Conventional methods are the optimal choice compared to the additive construction cost of $29,391.32. A key highlight in this comparison is the individual cost totals. The material cost for additive construction was 59% of the conventional cost. Additionally, labor cost had a 31% cost savings over conventional construction. The key differentiator was the transportation cost. The flight hour cost significantly increases the total cost of the project for each hour of flight time.

A sensitivity analysis demonstrates the distance at which additive construction would have been more advantageous. Figure 5 illustrates this sensitivity analysis and shows that the breakeven point is 736.1 kilometers. Any distance below that point would make additive construction the optimal construction choice. Since Camp Pendleton is 3,058 kilometers from Champaign, Illinois, conventional construction is the optimal method. Alternatively, the equipment may be driven across country from Champaign, Illinois, to Camp Pendleton, California. The cost of this alternative is $10,685.69 as quoted from ERDC-CERL, which would make it more cost effective than the conventional construction approach. Note that the window for sensitivity would be larger than shown due to extra construction steps included in the additive construction process that were not accounted for in the conventional construction calculation

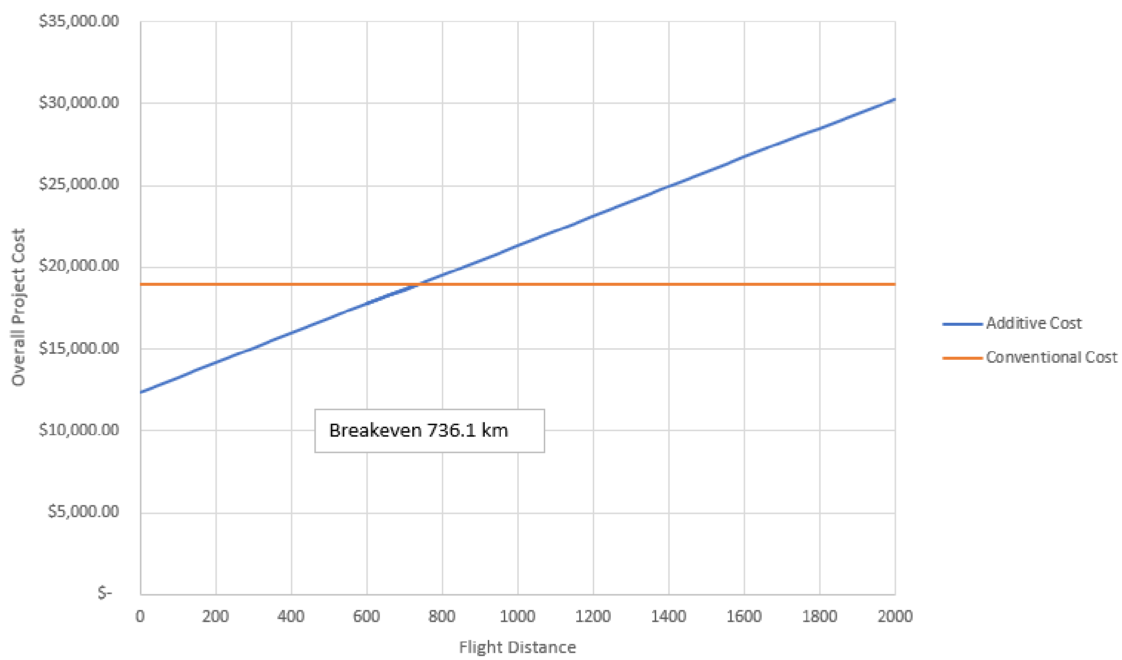

Figure 5. Case Study 2 Breakeven Point Graph

Discussion

The purpose of this discussion is to display the capabilities of the decision-making model. In this scenario, a 185.8 square meter facility is being constructed at a fictitious location called Site A. This site will be located in Iraq for accounting purposes. The local source of the material is located 24.1 kilometers from the project location. This project location does not have an airfield. The closest airport is 48.3 kilometers from the project site. Site B is the staging location for the additive construction equipment. The distance between the two airports is 3,497 kilometers. The conventional method requires a cement truck. The comparison is for the exterior walls only and will not include interior work, roof, or foundations.

The material requirements for additive construction are concrete and reinforcing materials that are locally sourced. The printing equipment coming from Site B has no upfront costs. Table 12 shows the list of locally sourced materials that bring the total material cost (M_5) to $13,127. These quantities are scaled from Case Study 1 from a 47.6 square meter building to 185.8 square meter; local prices would need to be obtained for a more definitive estimate.

Table 12. Discussion Additive Material

Item	Qty	Unit Volume	Unit Weight	Unit Cost	Total Volume	Total Weight	Total Cost
Concrete	937.5	0.125	94	$10.00	117.1875	88125	$9,375.00
Reinforcement Material	3350	0.25	1	$1.12	837.5	3350	$3,752.00
						M_5	**$13,127.00**

The transportation cost for additive construction for this fictitious site differs from the previous case studies in that the project location does not have an airfield. For this reason, the imported material requires air transportation and ground transportation. As previously stated, Site A is in Iraq. The average fuel cost in Baghdad, Iraq, is $0.51 per liter ("Iraq gasoline prices, 11-Jan-2021 | GlobalPetrolPrices.com" n.d.). The usage cost of the flatbed truck for Iraq is assumed to be the United States' national average at a rate of $150.27 per vehicle. Table 13 shows the vehicles and their associated quantities. The total transportation cost (T_5) is $31,364.40.

Table 13. Discussion Additive Transportation

Vehicle	N_{VA}	C_{VG}	KPL or S_{Cr}	Distance	F_A or F_G	Total Cost
HC-130J	1	0	644	3497	$5,776.00	$31,3764.4
Flatbed Truck M_{LS}	2	$300.54	$3.00	24.1	$0.51	$308.73
Flatbed Truck M_{IM}	1	$150.27	$3.00	48.2	$0.51	$158.46
					T_5	**$31,364.40**

The labor is consistent with all additive construction projects. Three workers are required to operate the printing equipment and its supply chain. Table 14 shows the

activity breakdown. For this site, the hourly requirement for each activity from Case Study 1 were scaled up. The total labor cost (L_5) is $12,600.

Table 14. Discussion Additive Labor

Activity	Hours	Unit Rate	Total Cost
Operations and Maintenance	168	$75.00	$12,600.00
		L_5	**$ 12,600.00**

The cost variables M_5, T_5, and L_5 are input into Equation 7. Adding these variables together results in a total cost of construction using additive construction of $57,558.60. The transportation cost is still high; however, with a larger-scale project, the transportation cost makes up a smaller portion of the overall project cost.

The conventional construction method uses all locally sourced materials and a concrete truck to deliver the concrete. The concrete cost is assumed to be consistent with the cost in Case Study 1 with the same load requirements. Ground transportation provided the remaining materials. Table 15 breaks down the material requirement. The total material cost (M_6) is $51,116.31.

Table 15. Discussion Conventional Material

Item	Qty	Unit Volume	Unit Weight	Unit Cost	Total Volume	Total Weight	Total Cost
Concrete	3129	8	94	$10.00	25032	294126	31,290.00
Formwork	5907	0.33	1.5	$0.33	1949.31	8860.5	$1,949.31
Form Support Material and Supplies	5625	0.33	1	$0.20	1856.25	5625	$1,125.00
Reinforcement Material	3350	0.25	1	$1.12	837.5	3350	$3,752.00
Concrete Truck	13	0	0	1,000.00	0	0	13,000.00
						M_6	**$51,116.31**

Since a concrete truck delivers the concrete, the concrete delivery's logistical cost is absorbed by the concrete truck's unit cost. The remaining material needs to be delivered by truck. The material specifications show that the delivery requires two flatbed trucks. With the average fuel cost in Iraq at $0.51 per liter and a usage cost of $300.54, the total transportation cost (T_6) is $308.73.

Once again, the formwork requires a significant amount of labor hours. The activity breakdown in Table 16 shows the concrete pour and reinforcement do not amount to the formwork's labor requirement. The total labor cost (L_6) to create a 185.8 square meter structure is $20,421.09.

Table 16. Discussion Conventional Labor

Activity	Hours	Unit Rate	Total Cost
Form Work	676.6	$21.50	$14,546.09
Concrete Pour	62.5	$35.00	$2,187.50
Reinforcement	125	$29.50	$3,687.50
		L_6	**$ 20,421.09**

The cost variables M_6, T_6, and L_6 are input into Equation 7. Adding these variables together results in a total cost of construction using conventional construction of $71,846.14. Additive methods are the optimal choice with a construction cost of $57,558.60. One factor that stands out is that the conventional method did not have much of a transportation cost due to being 100% locally sourced; if formwork materials such as plywood are unattainable locally, this would further increase the cost effectiveness of additive construction and increase the breakeven point. The material and labor cost of additive construction represented 36% of the cost of conventional methods. It was only the transportation cost that brought a closer equilibrium between the two methods.

A sensitivity analysis shows the breakeven point and the distance needed to erase the cost savings of using additive construction for a larger project. Figure 6 shows the comparison of the two construction methods depending on the distance from airport to airport. The breakeven point is at 5,107.7 kilometers; for any distance after that point, conventional construction is the more cost-effective method. The slope of the additive construction plot illustrates how rapidly costs can increase based on the flight distance. On the other hand, a large project such as this can show tremendous cost savings by minimizing the air travel distance. Figure 7 shows the maximum distance Site B can be from Site A to have additive construction be the most cost-effective option. In this example, Site B is 3,497 kilometers from the closest airport, falling inside the circle.

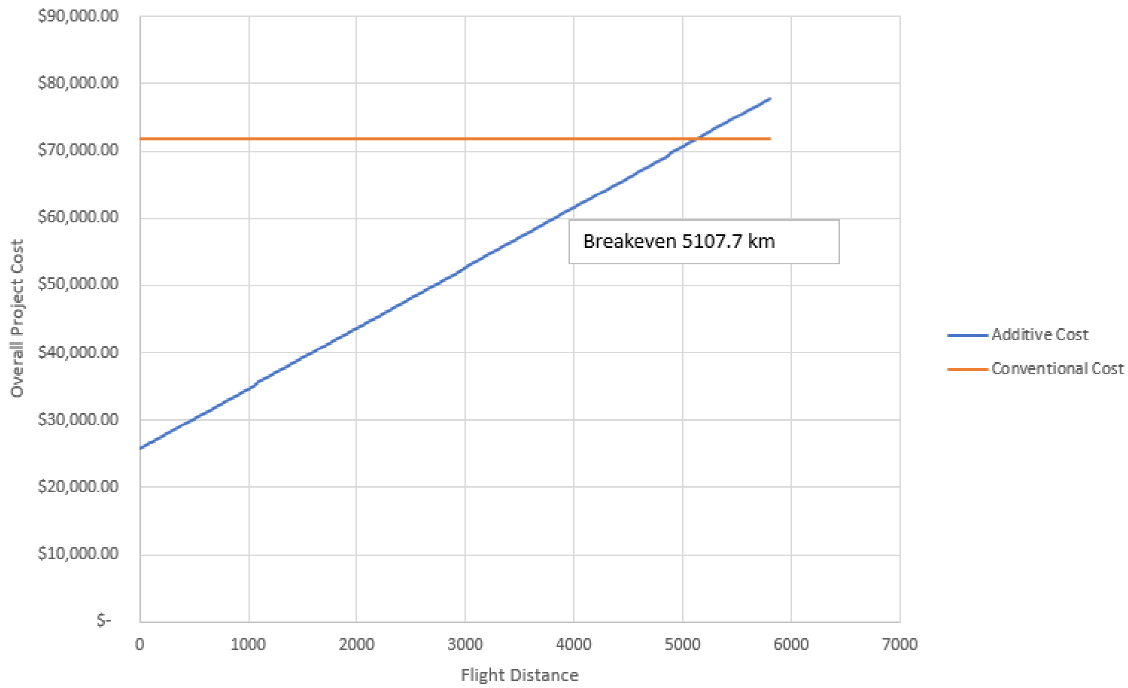

Figure 6. Discussion Breakeven Point Graph

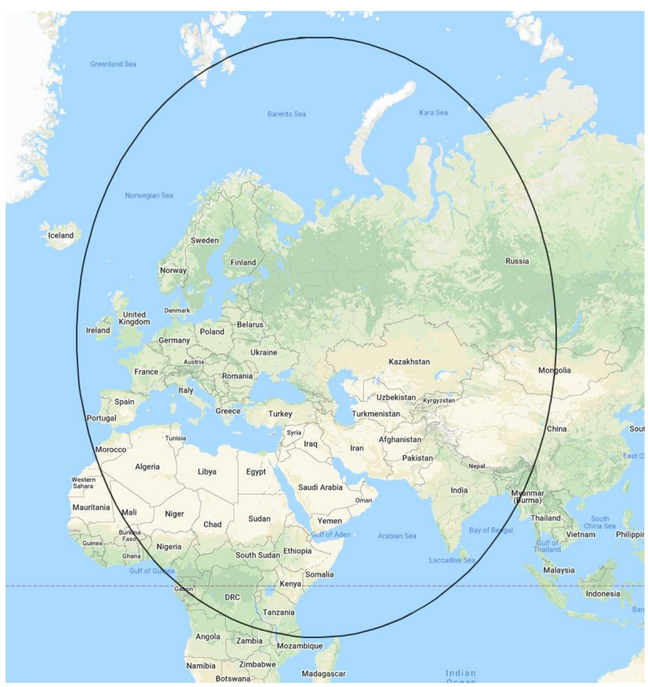

Figure 7. Site B Breakeven Limit

Additional consideration for additive construction is the staging location for equipment. Having multiple staging locations adds to deployability and feasibility of additive construction. Figure 8 shows the impact of staging equipment at various locations: Seattle, WA; Ramstein, Germany; Doha, Qatar; Gunsan, South Korea; and Guam. The circles illustrate breakeven distances for one (black), two (blue), and three (red) 47.6 square meter structures. The breakeven influence begins to overlap as the project size increases. This is seen in the Pacific between South Korea and Guam. This scenario stems from the need for multiple printers to reduce overall construction time in constrained environments.

Figure 8. Multiple Staging Locations

Investigative Questions Answered

The goal of this thesis is to answer investigative questions about comparing additive to conventional construction. The questions posed in Chapter I are repeated below for convenience.

1. What are the most critical variables driving the cost of construction projects?
2. How do critical variables vary between additive and conventional construction projects?
3. How does the distance affect the cost of the project and the construction method decision?
4. How do additive and conventional construction costs vary under different scenarios?

The variables found to affect construction projects' costs are material, logistics and transportation, and labor costs. The literature review found these factors to have the most significant effect on conventional construction methods that also play a large part in additive construction. The material and labor costs show a considerable reduction from conventional to additive construction; however, the transportation cost to fly the equipment to a project location increases the total project cost that has the potential to negate cost savings. The results show the transportation cost per flight hour has a significant effect on the overall cost. The cost savings with additive construction concerning labor and material can be negated by the increased transportation cost of flying in the equipment. Additive construction may be more advantageous in larger construction projects where the cost savings surpass the transportation cost to counteract the air transportation cost or where formwork materials are not readily available and have to be shipped long distance.

Summary

This section showcased two real-world additive construction case studies and compared them to conventional construction equivalents using a decision-making model. This model was then used to estimate the most cost-efficient construction method for a fictitious project in Iraq. The case studies showed the material and labor costs were lower using additive construction. The ground transportation for each method did not vary too much as the vehicles were similar for both methods. On the other hand, air transportation had a significant impact on the total cost of a project. The sensitivity analyses showed smaller projects could have cost savings quickly erased with the printing equipment's air transportation cost in additive construction. As project sizes increase, the allowable distance increases to maintain the affordability of additive construction. For smaller projects at a distance higher than the breakeven point, conventional construction is the cost-effective method. However, this research is considered exploratory and should not be used for decision-making without further analysis.

V. Conclusions and Recommendations

The purpose of this chapter is to provide an overarching conclusion of the research and analysis. The findings from the research highlight the significant contributions to the progression of additive construction. Never before has there been a cost comparison tool for decision-making between additive and conventional construction. This research provides the development and analysis of a decision-making model for use in choosing a construction method. Additionally, this model offers an opportunity for further research in determining the optimal construction method. This model investigates the cost of each method strictly. Further research can expand to mold to individual situations. Lastly, the summary of this research is a significant stride in the progression of additive construction research. However, this research is considered exploratory and should not be used for decision-making without further analysis.

Conclusions of Research

The literature review showed that there is interest in innovative solutions in the construction industry. The increase in customer demands has pushed the construction industry to look for more efficient ways to build. Additive construction is an innovative method that shows promise to be viable. One of the keys to viability is the cost comparison between conventional and additive construction. The research found materials, logistics and transportation, and labor as key cost variables. This research identified key components to obtaining the material cost using real-world projects and RS Means, the industry-accepted cost estimating software. The unit cost, weight, and

volume combined with the quantity contributed to the total cost. The weight and volume aided in selecting the type and number of vehicles to get the material to the project site from the source. The chosen vehicles and the associated distances provided the transportation cost for the delivery. The final piece to the cost was the labor costs associated with the project. This information was obtained similarly using real-world projects and RS Means. This information gave an activity breakdown, hourly requirements, and the hourly pay for the skilled laborer.

The two case studies showed real-world projects for additive construction with the cost estimate to build a similar structure using conventional construction methods to assess the decision-making model. The discussion used this model with a fictitious scenario to demonstrate its application. The case study results showed significant cost savings in the material and labor costs associated with additive construction over conventional methods. The key differentiator between the two methods is the use of air transportation to import equipment and materials. The cost per flight hour for each airframe can make up a large portion of the overall project cost. Depending on the project's size, the cost savings attributed to additive construction can quickly diminish with the distance from the material source. Given that the printing equipment is not likely locally available, air transportation is unavoidable. The model and its sensitivity analysis allow decision-makers to determine the maximum distance acceptable to use additive construction for a specific project size.

This thesis focused on the external structure only. Conventional construction techniques are still required for the internal pieces, such as electrical, plumbing, and

HVAC systems. The cost comparison of the external structure is consistent with the engineering economics principle to focus on the differences between alternatives.

Significance of Research

The past research in additive construction focused on material composition and structural design. While this research has made it possible to construct structures using additive construction technology, it failed to provide a cost comparison between additive and conventional construction. Conversations with the U.S. Army Engineer Research and Development Center Construction Engineer Research Laboratory (ERDC-CERL) found frequent inquiries into additive versus conventional construction costs. This research identified vital components to answer these questions. The elements were broken down into obtainable variables that were consolidated to form a model to aid decision-makers in answering these questions. Real-world scenarios were used to build the model, while a fictitious case demonstrated the model's applicability. This research helps ERDC-CERL fill in the final piece to additive construction questions of "why, how, where, and how much."

Recommendations for Future Research

This research presents the framework to apply the model to contingency environments for military use. A potential addition to this research is developing a utility model to accompany this decision-making model. This model will allow decision-makers to prioritize each factor's importance as a recommended area of future research. For example, placing a utility attached to the total material, transportation, and labor costs would let decision-makers prioritize the importance of each component. If the

environment is hostile, there may be more emphasis on reducing a project's labor demands. Or, if materials are scarce, more emphasis could be placed on materials. Additional research is needed to put the utility variables in the right place.

This research highlighted transportation as a significant cost factor. This creates a future research opportunity regarding transportation cost. A linear optimization model using different transportation types and vehicles could help optimize the project's transportation cost. For example, transportation types are land, air, or sea. Using these methods, costs, and distances along with vehicle choices may provide an optimal combination to input into this research's decision-making model.

Summary

In summary, most research into additive construction has focused on the material composition and the structural design of the product. The question left unanswered concerned which method is more cost-effective. This research examined the key components that drive the price of both additive and conventional construction methods. The result was material, logistics and transportation, and labor costs being the primary factors to examine. As stated, there is significant research into the material composition and additives to provide a cementitious material that can fulfill additive construction requirements, workability, and layer bonding. ERDC-CERL has experimented with proprietary materials and locally sourced blends, choosing local materials for their cost-benefit and availability. Transportation and labor breakdowns for the project's overall cost using this material requires further attention.

This research utilized case studies from real-world scenarios as a starting point for developing a decision-making model for choosing the appropriate construction method. The case studies used additive construction methods. The conventional equivalents used project research and RS Means, an industry-accepted cost estimating software for development. This equivalent allowed for a direct comparison between the two methods for each scenario.

The breakdown of the total project cost also highlighted a variable that significantly impacted the cost outcome – the air transportation. The cost per flight hour is a constant that can substantially affect the project's overall cost; therefore, a sensitivity analysis determines the maximum distance to which additive construction is the more cost-effective construction method. The breakeven point is associated with a distance at which cost savings disappear.

The varying breakeven points highlight an implied takeaway that larger projects have a high breakeven point. This evidence also means that larger projects have higher cost savings within the material and labor variables. Minimizing air freight on large projects makes additive construction the cost-effective choice. This decision-making model guides the maximum distance at which a project should consider additive construction.

This research is considered exploratory and should not be used for decision-making without further analysis. However, the research provides decision-makers insight into critical factors to consider when contemplating additive construction for their project.

Appendix

Case Study 1 Additive Construction

Material and Equipment

Locally Sourced Material and Equipment — M_{LS}= $ 5,960.51

Item	Qty	Unit Vol	Unit Wt	Unit Cost	Total Vol	Total Wt	Total Cost
Concrete	500	0.125	94	$ 10.00	62.5	47000	$ 5,000.00
Reinforcement Material	857.6	0.25	1	$ 1.12	214.4	857.6	$ 960.51
					0	0	$ -
					0	0	$ -

Imported Material and Equipment — M_{Im}= $ -

Item	Qty	Unit Vol	Unit Wt	Unit Cost	Total Vol	Total Wt	Total Cost
Printing Equipment	1	11.1	3000	$ -	11.1	3000	$ -
					0	0	$ -
					0	0	$ -
					0	0	$ -

Transportation

Air Transportation — T_A= $ -

Vehicle	Max Vol	Max Wt	Req Vol	Req Wt	Qty (N_{VA})	Cruising Speed (KPH)	Distance (Km)	Fuel Cost Per Flight Hour	Total Cost
HC-130J	82.38	25000	11.1	3000	1	644		$ 5,776.00	$ -
					0				$ -
					0				$ -

Ground Transportation — T_G= $ 500.93

Vehicle	Max Vol	Max Wt	Req Vol	Req Wt	Qty (N_{VG})	Usage	Km Per Liter (KPL)	Distance (Km)	Fuel Cost Per Liter	Total Cost
Flatbed Truck	98.2	48000	276.9	47857.6	3	$453.27	$ 3.00	64.4	$ 0.74	$ 500.93
					0	0				$ -
					0	0				$ -

Labor

Activity	Hours (H_{AC})	Unit Rate (C_{AC})	Total Cost
Operations and Maintenance	16.75	$ 75.00	$1,256.25
			$ -
			$ -
			$ -

Total Costs

Total Materal Cost (M)	$ 5,960.51
Total Transportation Cost (T)	$ 500.93
Total Labor Cost (L)	$ 1,256.25
Total Cost	**$ 7,717.69**

Case Study 1 Conventional Construction

Material and Equipment

Locally Sourced Material and Equipment — M_{ls} = $ 9,757.47

Item	Qty	Unit Vol	Unit Wt	Unit Cost	Total Vol	Total Wt	Total Cost
Concrete	801	0.125	94	$ 10.00	100.125	75294	$ 8,010.00
Formwork	1512	0.0093	1.5	$ 0.33	14.0616	2268	$ 498.96
Form Support Material and Supplies	1440	0.0093	1	$ 0.20	13.392	1440	$ 288.00
Reinforcement Material	857.6	0.007	1	$ 1.12	6.0032	857.6	$ 960.51

Imported Material and Equipment — M_{lm} = $ -

Item	Qty	Unit Vol	Unit Wt	Unit Cost	Total Vol	Total Wt	Total Cost
					0	0	$ -
					0	0	$ -
					0	0	$ -
					0	0	$ -

Transportation

Air Transportation — T_A = $ -

Vehicle	Max Vol	Max Wt	Req Vol	Req Wt	Qty (N_{VA})	Cruising Speed (MPH)	Distance (Km)	Fuel Cost Per Flight Hour	Total Cost
			0	0	0				$ -
					0				$ -
					0				$ -

Ground Transportation — T_G = $ 333.95

Vehicle	Max Vol	Max Wt	Req Vol	Req Wt	Qty (N_{VG})	Usage	Km Per Liter (KPL)	Distance (Km)	Fuel Cost Per Liter	Total Cost
Flatbed Truck	98.2	48000	133.5818	79859.6	2	$ 302.18	$ 3.00	64.4	$ 0.74	$ 333.95
					0	0				$ -
					0	0				$ -

Labor

Activity	Hours (H_{AC})	Unit Rate (C_{AC})	Total Cost
Form Work	173.2	$ 21.50	$3,723.80
Concrete Pour	16	$ 35.00	$ 560.00
Reinforcement	32	$ 29.50	$ 944.00
			$ -

Total Costs

Total Materal Cost (M)	$ 9,757.47
Total Transportation Cost (T)	$ 333.95
Total Labor Cost (L)	$ 5,227.80
Total Cost	**$ 15,319.22**

Case Study 2 Additive Construction

Material and Equipment

Locally Sourced Material and Equipment — M_{LS}= $ 6,400.00

Item	Qty	Unit Vol	Unit Wt	Unit Cost	Total Vol	Total Wt	Total Cost
Cement	240	0.125	94	$ 10.00	30	22560	$ 2,400.00
Aggregate	40	0.3328	2000	$ 100.00	13.312	80000	$ 4,000.00
					0	0	$ -
					0	0	$ -

Imported Material and Equipment — M_{Im}= $ -

Item	Qty	Unit Vol	Unit Wt	Unit Cost	Total Vol	Total Wt	Total Cost
Printing Equipment	1	11.1	3000	$ -	11.1	3000	$ -
					0	0	$ -
					0	0	$ -
					0	0	$ -

Transportation

Air Transportation — T_A= $ 17,040.99

Vehicle	Max Vol	Max Wt	Req Vol	Req Wt	Qty (N_{VA})	Cruising Speed (KPH)	Distance (Km)	Fuel Cost Per Flight Hour	Total Cost
HC-130J	82.38	25000	11.1	3000	1	644	1900	$ 5,776.00	$ 17,040.99
					0				$ -
					0				$ -

Ground Transportation — T_G= $ 550.32

Vehicle	Max Vol	Max Wt	Req Vol	Req Wt	Qty (N_{VG})	Usage	Km Per Liter (KPL)	Distance (Km)	Fuel Cost Per Liter	Total Cost
Flatbed Truck	98.2	48000	43.312	102560	3	455.01	$ 3.00	64.4	$ 1.48	$ 550.32
					0					$ -
					0					$ -

Labor

Activity	Hours (H_{AC})	Unit Rate (C_{AC})	Total Cost
Operations and Maintenance	72	$ 75.00	$5,400.00
			$ -
			$ -
			$ -

Total Costs

Total Materal Cost (M)	$ 6,400.00
Total Transportation Cost (T)	$ 17,591.32
Total Labor Cost (L)	$ 5,400.00
Total Cost	**$ 29,391.32**

Case Study 2 Conventional Construction

Material and Equipment

Locally Sourced Material and Equipment — M_{LS}= $ 10,920.00

Item	Qty	Unit Vol	Unit Wt	Unit Cost	Total Vol	Total Wt	Total Cost
Concrete	600	8	94	$ 10.00	4800	56400	$ 6,000.00
Forms	600	1	1.5	$ 3.20	600	900	$ 1,920.00
Concrete Truck	3	0	0	$1,000.00	0	0	$ 3,000.00
					0	0	$ -

Imported Material and Equipment — M_{Im}= $ -

Item	Qty	Unit Vol	Unit Wt	Unit Cost	Total Vol	Total Wt	Total Cost
					0	0	$ -
					0	0	$ -
					0	0	$ -
					0	0	$ -

Transportation

Air Transportation — T_A= $ -

Vehicle	Max Vol	Max Wt	Req Vol	Req Wt	Qty (N_{VA})	Cruising Speed (KPH)	Distance (Km)	Fuel Cost Per Flight Hour	Total Cost
			0	0	0				$ -
					0				$ -
					0				$ -

Ground Transportation — T_G= $ 199.05

Vehicle	Max Vol	Max Wt	Req Vol	Req Wt	Qty (N_{VG})	Usage	Km Per Liter (KPL)	Distance (Km)	Fuel Cost Per Liter	Total Cost
Flatbed Truck	3468	48000	600	900	1	167.28	$ 3.00	64.4	$ 1.48	$ 199.05
					0	0				$ -
					0	0				$ -

Labor

Activity	Hours (H_{AC})	Unit Rate (C_{AC})	Total Cost
Form Work	106.8	$ 40.00	$4,272.00
Concrete Pour	118.72	$ 30.00	$3,561.60
			$ -
			$ -

Total Costs

Total Materal Cost (M)	$ 10,920.00
Total Transportation Cost (T)	$ 199.05
Total Labor Cost (L)	$ 7,833.60
Total Cost	**$ 18,952.65**

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14. ABSTRACT

Additive construction is a potential game changing innovative alternative to conventional methods with regards to structural integrity, timeliness, and waste reduction, especially in remote locations. While there have been numerous studies into the material science, additive construction will not be a viable alternative until a cost analysis is performed. This paper details the cost elements for both methods. Breaking down the key variables of material, logistics and transportation, and labor costs garner a better understanding of the cost difference between the two construction methods

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