3-2020

An Analysis of the Viability of 3D-Printed Construction as an Alternative to Conventional Construction Methods in the Expeditionary Environment

Jeneé A. Jagoda

AN ANALYSIS OF THE VIABILITY OF 3D-PRINTED CONSTRUCTION IN THE EXPEDITIONARY ENVIRONMENT

THESIS

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AFIT-ENV-MS-20-M-217

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Wright-Patterson Air Force Base, Ohio

AFIT-ENV-MS-20-M-217

AN ANALYSIS OF THE VIABILITY OF 3D-PRINTED CONSTRUCTION AS AN ALTERNATIVE TO CONVENTIONAL CONSTRUCTION METHODS IN THE EXPEDITIONARY ENVIRONMENT

THESIS

Presented to the Faculty

Department of Systems Engineering and Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering Management

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March 2020

DISTRIBUTION STATEMENT A.
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AFIT-ENV-MS-20-M-217

AN ANALYSIS OF THE VIABILITY OF 3D-PRINTED CONSTRUCTION IN THE EXPEDITIONARY ENVIRONMENT

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AFIT-ENV-MS-20-M-217

Abstract

Conventional construction is believed by some to have reached its technological limit of performance, making it increasingly difficult for conventional construction methods to meet the U.S. military's core standards of quality, cost, and timeliness in the expeditionary environment. While still in its infancy, 3D-printed construction has the potential to revolutionize the way the military performs construction in deployed environments. This research conducts a systematic review of the viability of 3D-printed construction to investigate whether or not it is now or could be a viable replacement for conventional construction methods, specifically in remote environments where conventional construction capability may be limited. This research then evaluates seven key viability factors – materials, structural design, process efficiency, logistics, labor, environmental impact, and cost – as they apply to two recent, military-run 3D-printed construction case studies, before drawing conclusions regarding the current viability of 3D-printed construction. Finally, this research suggests areas in which further research and development is needed in order to ensure the effectiveness of 3D-printed construction in the expeditionary environment.

Acknowledgments

First, I would like to express my appreciation to my husband – I am so grateful we had the opportunity to attend AFIT together. Thank you for supporting me in my research, keeping me accountable in my classes, and holding down the fort at home each time I was TDY. To my advisor, Major Steven Schuldt: thank you for choosing to take me on as an advisee. Over the last eighteen months, you went above and beyond by providing me with invaluable feedback on my research and encouraging me to take advantage of special opportunities during my time at AFIT. To my committee members, Megan Kreiger and Brandy Diggs-McGee, thank you for allowing me to shadow you at the Army Engineer Research and Development Center - Construction Engineering Research Laboratory and learn from your 3D printing expertise. To my sponsors, the Air Force Civil Engineer Center, Air National Guard, and United States Army Corps of Engineers; thank you for taking an interest in my research and funding my research travel, conferences, and publications. And finally, to my classmates, the GEM Class of 20M – you are what I will remember most about my AFIT experience. I have so much respect for each of you and am incredibly grateful the Air Force allowed our paths to cross in this assignment!

Jeneé A. Jagoda

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AN ANALYSIS OF THE VIABILITY OF 3D-PRINTED CONSTRUCTION IN THE EXPEDITIONARY ENVIRONMENT

I. Introduction

Background

Historically, the construction industry is slow to adopt new technologies due to the perceived risks of implementing newly developed, untested products and methods [1]. Conventional construction – the use of manually operated tools and equipment and traditional building methods – is believed by some scholars to have reached its technological limit of performance [2]. Consequently, it is increasingly difficult for conventional construction companies to meet customers' core standards of quality, cost, and timeliness [3,4]. Over the last few decades, the construction industry saw reduced profit margins and stagnating productivity in comparison to other mainstream industries [5]. While still in its infancy, three-dimensional (3D) printed construction is a promising technology with the potential to revolutionize the construction industry.

3D-printed construction is an advanced, additive construction process capable of producing a wide range of complex structures and geometries without formwork using a layer-by-layer material deposition approach [6–8]. The construction industry has used 3D printing to successfully build residential homes, apartment buildings, hotels, office buildings, and bridges [6,9]. It holds great promise for the construction industry due to its potential ability to lower total costs, shorten construction duration, improve quality and consistency, decrease labor requirements, reduce material utilization, increase

customization, promote work flexibility, enhance sustainability, eliminate the need for formwork, and enable construction in harsh environments [4,6,8,10,11].

This thesis investigates whether or not 3D-printed construction is now or could be a viable replacement for conventional construction methods, specifically in the expeditionary environment found on overseas military deployments. Expeditionary construction requirements include pavements and structures such as troop barracks and hardened aircraft shelters. This research investigates seven areas of viability: materials, structural design, efficiency, labor, logistics, environmental impact, and cost.

Problem Statement

In 2015, the Air Force released its thirty-year Strategic Master Plan, which shapes the future direction of the Air Force through the establishment of five vectors [12]:

1. Provide Effective 21st-Century Deterrence.
2. Maintain a Robust and Flexible Global Intelligence, Surveillance, and Reconnaissance (ISR) Capability.
3. Ensure a Full-Spectrum Capable, High-End Focused Force.
4. Pursue a Multi-Domain Approach to our Five Core Missions.
5. Continue the Pursuit of Game-Changing Technologies.

To fulfill the final vector of the Strategic Master Plan, "Continue the Pursuit of Game-Changing Technologies," [12] the Air Force Civil Engineer Center (AFCEC) and Headquarters Air Force Civil Engineers (HAF/A4C) are interested in determining the immediate and future viability and return on investment of 3D-printed construction of temporary and semi-permanent structures in the expeditionary environment. The Air Force is often risk-averse when it comes to changing proven methods; however, the

results of this study could determine whether to replace conventional construction with 3D-printed construction and, if so, what to consider in its implementation. Previous Air Force 3D printing research was limited to small-scale applications [13,14]; this is the first Air Force-sponsored research to investigate construction-scale applications and build upon other military branches' 3D-printed construction research.

Contrary to the Air Force's recent interest in 3D printing, the Army has a history of investing time, money, and talent into 3D-printed construction research. The United States Army Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL) established the Automated Construction of Expeditionary Structures (ACES) program in 2015 to develop the capability to print custom-designed expeditionary structures in the field, on-demand, using locally available materials [15]. The goals of the ACES program include minimizing labor requirements, decreasing material usage, reducing the logistical demand and supply train in the expeditionary environment, and building stronger, more durable structures. The ACES program has developed multiple construction-scale 3D printers and printed two concrete buildings and one reinforced concrete bridge, as shown in Figure 1 [16–18].

(a) (b) (c)

Figure 1. Past ACES Prints: (a) Barracks Hut (B-Hut) 1 completed August 2017; (b) B-Hut 2 completed August 2018; (c) 10m pedestrian bridge completed December 2018.

In the past, the Navy and Marine Corps have both partnered with the Army to demonstrate the capability of 3D-printed construction, with the goal of establishing a program of record (a program approved and funded by the Future Year Defense Program) for 3D printing by 2021 [19,20]. The Marine Corps is the least risk-averse of all of the military branches and is interested in 3D-printed construction as a way to modernize its engineering capabilities, accomplish more in-house with less dependence on its sister services, and minimize its footprint overseas. The Marine Corps' interest in 3D-printed construction and need for intuitive, straightforward construction equipment that is portable, compatible with local materials, and easy to troubleshoot and repair has helped drive the Army Corps of Engineers' research and development into 3D-printed construction. Based on the success of the ACES program and research progress made by its sister services, the Air Force is interested in initiating its own research and development program for 3D-printed construction. This thesis aims to help shape the course of that program by identifying areas of focus and a possible way forward.

Research Objectives

Given the intent of this thesis – to provide an understanding of the potential viability of 3D-printed construction in the expeditionary environment – the research objectives are as follows:

1. Systematically review the available literature to identify the primary viability considerations affecting 3D-printed construction, compare the benefits and challenges of 3D-printed construction versus conventional construction, and establish a framework to guide future research and development.

2. Analyze two recent case studies of military 3D-printed construction to identify specific lessons learned and future viability considerations.

Thesis Organization

This thesis follows a scholarly format in which chapters 2, 3, 4, and 5 each serve as stand-alone academic conference or journal publications. In Chapter 2, "A Review of Reviews: Assessing the Viability of 3D-Printed Construction," a high-level overview of recent academic literature establishes a framework to determine the viability of different construction methods by identifying seven factors influencing the successful adoption and implementation of 3D-printed construction. This conference paper highlights the benefits and challenges faced by each viability factor and suggests areas requiring further research and investment. This paper was published in the Proceedings of the 1st International Conference on 3D Printing and Transportation, held in November 2019 in Washington, D.C.

Chapter 3, "A Systematic Review of the Viability of 3D-Printed Construction," builds off of the viability framework established in Chapter 2 by conducting a systematic review of current academic literature. This review highlights existing 3D printing methods and applications and summarizes the seven factors with the greatest influence on the viability of 3D-printed construction: materials, structural design, efficiency, labor, logistics, environmental impact, and cost. The systematic review used the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology to narrow 3,799 Scopus search results to 247 relevant articles [21,22]. This journal article aims to compare and contrast the benefits and challenges of 3D-printed construction versus conventional construction to facilitate a decision of which method to implement in

the expeditionary environment. Finally, Chapter 3 discusses current research gaps and limitations and suggests areas of future research to further establish the viability of 3D-printed construction. The target journal for this paper is *Automation in Construction*, an international peer-reviewed journal published by Elsevier with an impact rating of 4.313 [23].

The next two chapters apply knowledge obtained through the systematic review process to assess the benefits, challenges, and viability concerns of two recent military 3D-printed construction case studies. Chapter 4, "The Benefits and Challenges of On-Site 3D-Printed Construction: A Case Study," highlights a tri-service exercise that took place at Camp Pendleton Marine Corps Base, California in December 2018 to demonstrate the current capabilities of military 3D-printed construction. In this exercise, the Army Corps of Engineers transported ACES Lite, a 3D printer developed under a cooperative research and development agreement with Caterpillar, from Champaign, Illinois to Camp Pendleton, where all material preparation and construction occurred on site in field conditions. This conference paper examines the materials and methods used to 3D print a 10-meter concrete bridge, challenges encountered in the process, and lessons learned. Finally, Chapter 4 focuses on future opportunities to automate the 3D printing process and lessen labor demand. This paper was published in the proceedings of the 3rd International Conference on Engineering Technology and Innovation, held in April 2019 in Belgrade, Serbia.

Chapter 5, "The Viability and Simplicity of 3D-Printed Construction: A Case Study," highlights a second tri-service exercise that took place at the U.S. Army ERDC-CERL in Champaign, Illinois in November 2019 to demonstrate the viability and

simplicity of military 3D-printed construction in a controlled environment. In this exercise, an updated version of the 3D printer used in the bridge print, ACES Lite 2, was used to construct three concrete dragon's teeth (square pyramid military fortifications used to defend against tanks and armored vehicles) and two 3D-printed concrete masonry units. This conference paper examines the viability of using 3D-printed construction in a deployed military environment by considering the benefits and challenges associated with the printing materials, structural design, process efficiency, labor demands, logistical considerations, environmental impact, and project cost. Chapter 5 also focuses on future applications and areas of further research for 3D-printed construction. The target journal for this paper is *Infrastructures*, an international peer-reviewed journal published by MDPI. Finally, Chapter 6 outlines conclusions and suggested follow-on research.

II. A Review of Reviews: Assessing the Viability of 3D-Printed Construction

Jeneé A. Jagoda, Steven J. Schuldt

Abstract

While still in the early stages of development, 3D-printed construction displays the potential to address issues and challenges faced by conventional construction by lowering total costs, decreasing labor requirements, eliminating the need for formwork, reducing material utilization, increasing customization, shortening construction duration, and enhancing sustainability. This review examines the viability of 3D-printed construction by synthesizing eleven review articles on 3D printing authored between 2015 and 2018. It focuses on the benefits and challenges that labor requirements, material considerations, structural design, construction efficiency, supply and transportation requirements, and environmental impact pose to overall cost and viability. With continued investment in research and development, 3D printing could foreseeably become a viable and accepted method of construction in the near future; transforming the way the industry manages costs, labor, materials, scheduling, customization, and sustainability.

Introduction

Three-dimensional (3D) printing is an advanced additive manufacturing process that uses a layer-by-layer material deposition approach to produce a range of complex structures and geometries without formwork [6–8]. While still in its infancy, 3D-printed construction displays the potential to address issues and challenges faced by conventional construction by lowering total costs, decreasing labor requirements, eliminating the need for formwork, reducing material utilization, increasing customization, shortening

construction duration, and enhancing sustainability [4,6,8,10,11]. It is capable of greater strength and density than conventionally cast components and can be used in more complex structural applications [24,25]. One study hails 3D printing as one of the most significant and transformative technologies of the 21st century; another designates it a disruptive technology because it delivers a leap in performance compared to conventional construction methods [6,26]. This review analyzes factors affecting the overall viability of 3D printing in the construction of transportation and infrastructure networks and suggests areas for future research.

Methodology

This review examines the viability of 3D-printed construction by synthesizing eleven review articles on 3D printing authored between 2015 and 2018. Each review was thoroughly screened for any factors positively or negatively influencing the implementation of 3D printing in the construction industry. Working backward from the review articles yielded a total of 29 sources.

Findings

The potential of 3D printing to reduce construction costs is one of the most important factors determining the fate of its implementation by the construction industry [4]. Labor requirements, material considerations, structural design, construction efficiency, supply and transportation requirements, and environmental impact all contribute to overall cost and viability (Figure 2). The Venn Diagram also depicts the strongest relationships between each of the viability factors: adjacent factors (e.g. Materials and Environmental Impact) have greater interdependency than factors located on opposite sides of the diagram (e.g. Materials and Labor).

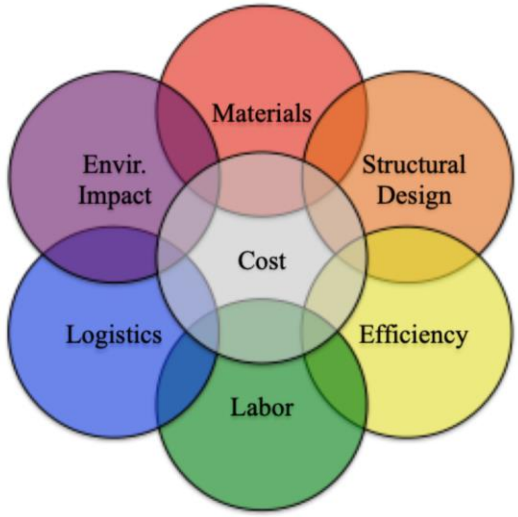

Figure 2. Venn Diagram Depicting the Relationship Between Cost and Viability. The top two benefits and single greatest challenge of each factor are outlined (Table 1) and discussed in greater detail within this section.

Table 1. Top Benefits and Challenge of Each Viability Factor.

	Benefit	**Benefit**	**Challenge**
Labor	Safety	Automation	Specialization
Materials	No Formwork	Alt. Sources	Consistency
Structure	Complexity	BIM Optimization	Lack of Standards
Efficiency	Reduced Build Time	Constant Operation	Speed vs. Strength
Logistics	Reduced Lead Time	Short Supply Chain	Portability vs. Size
Environment	Less Resources	Less Emissions	Insufficient Impact

Labor

The construction industry is one of the most dangerous, with a higher rate of injury, illness, and fatality than other industries due to hazards such as eye, skin, and respiratory tract irritation; chemical burns; slips, trips, and falls; and overexertion [27]. Approximately 4% of construction workers are injured in the United States each year [25]. However, as construction becomes increasingly automated, the quantity of laborers

needed – and the associated number of injuries incurred – decreases, helping to eliminate risk and reduce costs associated with both the labor and the injury or fatality [6,7,28]. For example, WinSun, a Chinese company, claimed it slashed labor costs by 50% to 80% using 3D printing to construct the Dubai Future Foundation office building [9,29]. Automation is becoming increasingly necessary as the workforce ages, leading to skilled labor shortages and difficulty recruiting a qualified workforce [9,24,30].

Studies have shown that rather than completely eliminating the need for a construction workforce, automation makes remaining jobs more specialized, favoring workers with higher levels of skill and creativity [26,31]. 3D printing requires skilled workers to integrate robotic and civil work together and may involve re-training [7]. This new skillset helps to promote gender equality in a male-dominated industry by changing the emphasis from physical strength and skill to cognitive and creative ability [32].

Materials

Because 3D-printed materials can retain their shape without formwork, the elimination of formwork is likely the most tangible cost benefit of 3D printing. Formwork, molds, and scaffolding typically account for 35% to 60% of the total cost of a concrete structure, depending on size and complexity [7,30,33]. Eliminating formwork saves time, lessens the labor demand, and conserves materials [5]. 3D printing can further cut material costs by using locally sourced, readily available, naturally occurring, or recycled materials; accurately predicting material needs to reduce unnecessary waste; and avoiding over-engineering [5,25,28,34,35].

Research on the properties of printed concrete is limited and designs constructed of other materials under different conditions need to be assessed for overall material and

structural quality [30,34]. The future success of 3D-printed construction will hinge on the development of a wide range of suitable material mixes in order to achieve consistent and repeatable rheological properties (properties of materials in their liquid or soft state) in a variety of applications and ensure compatibility with material storage, delivery, and deposition, taking into account the printer limitations [5,7,10,24,25].

Structural Design

One major advantage of 3D printing is its ability to produce components of increased complexity by either printing them directly or creating a leave-in-place, reusable, or insulating formwork [36,37]. 3D printing is largely complexity independent, enabling the production of highly customized components at minimal additional expense [5,10,25,26]. Currently, it is most profitable for complex structures and less cost-effective than conventional construction for simple structures [5,9]. Another advantage of 3D printing is that building information modeling optimizes the material, weight, and cost of every member based upon its required structural performance, unlike conventional construction, which often optimizes construction simplicity by making every member the same size, regardless of load demands [9].

At this time, minimal regulatory guidance exists to establish quality and process standards for the 3D printing industry. It is difficult for 3D printing technology to meet existing building codes; however, the establishment of new codes is expensive, time-consuming, and forces construction entities to adopt new materials and processes [4,9,38]. However, if established, these regulations can positively influence the level of organizational support for, and industry acceptance of, 3D printing technology [4,11].

Efficiency

3D printing can significantly reduce construction time [8,28]. Theoretically, concrete 3D printing could be capable of printing 1 ft^2 (0.09 m^2) of wall in less than 20 seconds, an entire room in an hour, and a 2,150 ft^2 (200 m^2) house in 24 hours, with an unknown total elapsed time for construction [37]. This rate of production is achieved by improving project planning, labor flow reliability, construction flexibility, and efficiency; streamlining the scheduling process; reducing lead time to production; and erasing the time required for formwork construction and inspection [6,28]. As the technology continues to develop, it could also eliminate the time spent placing reinforcement and installing utilities [6]. Another reason for these shortened construction times is that in an ideal environment, 3D printing methods operate at a steady, unrelenting pace, without requiring breaks for worker rest or curing [28].

Two key factors contributing to total print time are print speed and layer cycle time. Print speed is limited by the rate of material flow – particularly when undergoing a change in direction, such as at corners – and by printing precision: faster speeds have lower resolution and larger layer thickness, and vice versa [24,25,28,30,39]. Additionally, faster print speeds encourage bonding, while greater layer cycle time increases strength by allowing layers to develop enough stability to support both self-weight and the weight of subsequent layers [32]. However, the cycle time between layers must be carefully controlled to promote early strength while also avoiding cold joints [5]. These factors force a tradeoff between construction time and structural strength.

Logistics

3D printing can shorten the supply chain by enabling the immediate construction of critical or time-sensitive building components, reducing the need for order lead-time or expedited delivery [9,32]. By bringing the supplier closer to the customer, 3D printing mitigates productivity issues associated with late deliverables and removes the possibility that pre-fabricated concrete elements are damaged in transit, requiring repair upon delivery [26,40]. The use of locally sourced, readily available materials such as concrete also helps to minimize the supply chain, eliminating the requirement for ordering and shipping materials over large distances [11].

While on-site 3D-printed construction may be easier and more affordable than off-site pre-fabrication, both its process and materials must be weather-independent since environmental conditions affect the quality of completed construction [26,32,41]. Another consideration affecting the viability of 3D printing for a given application is the tradeoff between the portability of the machine and its available printing size, which may limit area and volume [32].

Environmental Impact

The construction industry consumes one-third of earth’s resources and accounts for 40% of global energy consumption, 40% of total solid waste generation, and 38% of overall greenhouse gas emissions [5,10]. 3D printing enables sustainable design and waste reduction by facilitating precise placement of materials and decreasing overall material usage [6]. It decreases energy use, resource demands, and carbon dioxide emissions by dramatically reducing material waste, human error, and the use of heavy machinery, construction equipment, and job-related vehicle transportation [4,10,42].

While the positive environmental impact of 3D printing increases with design complexity, overall, the impact of the construction process is much lower than the impact of material production [5,43]. One study showed the energy demand of a 3D printer used to construct a concrete wall was negligible compared to the overall environmental impact of the wall, the majority of which came from the production of concrete and reinforcing steel [44]. While it is possible for 3D-printed construction to have near zero waste and zero emissions if electricity is used to power the printer, material production – particularly concrete – generates large amounts of carbon dioxide [6]. This has prompted research into alternative materials that are more sustainable and have a longer service life.

Conclusion

While 3D printing shows promise in the construction industry, some of its greatest potential benefits also pose its most significant challenges. Despite making considerable research progress over the past twenty years, 3D-printed construction still faces obstacles pertaining to cost, material rheology, structural integrity, print resolution, process scalability, suitability to adverse environments, and standardization [6,7,10,24,32]. A multi-disciplinary research approach is necessary to resolve these barriers; however, research efforts are hindered by the proprietary nature of many proof-of-concept technologies, which lack publicly available information on methodology and results for evaluation and comparison [9,32]. Critical areas requiring further research are outlined (Table 2).

Table 2. Suggested Areas for Further Research.

	Suggested Research Areas
Materials	Mix Optimization, Use of Additives, Mixing Methods, Alt. Materials
Structure	Automation of Reinforcement, Utilities, Windows/Doors, Roofs; Load-Bearing Capacity & Strength; Anisotropic Behavior; Printing Voids
Logistics	Transportation Costs/Rqmts, Time to Assemble, Maintenance Schedule, Supply Costs/Rqmts
Environment	Life-Cycle Analysis, Green Materials, Circular Model

With continued investment in research and development, 3D printing could foreseeably become a viable and accepted method of construction in the near future; transforming the way the industry manages costs, labor, materials, scheduling, customization, and sustainability.

III. A Systematic Review and Analysis of the Viability of 3D-Printed Construction in Remote Environments

Jeneé A. Jagoda, Andrew J. Hoisington, Justin D. Delorit, Steven J. Schuldt

Abstract

3D-printed construction is an additive, layer-by-layer construction method with the potential to reduce material consumption, optimize design, decrease construction time, lower labor requirements, minimize logistical demand, improve sustainability, and reduce costs as compared to conventional construction. This paper presents the results of a systematic review of 3,699 publications spanning from January 1998 to June 2019. The review is focused on the viability of 3D-printed construction as a replacement for conventional construction methods, specifically in remote, isolated, or expeditionary environments, where conventional construction capability may be limited. The paper includes an analysis and characterization of the existing body of 3D-printed construction literature, before evaluating seven viability factors of the method: materials, structural design, process efficiency, logistics, labor, environmental impact, and cost. Next, the paper highlights three case studies of 3D-printed construction in remote, isolated, and expeditionary environments. The paper concludes by suggesting areas of future research to ensure the viability of this technology, such as printing full-scale structures and components with locally sourced materials in uncontrolled environments, defining standards for 3D printing, automating additional construction processes, and performing both environmental impact and cost life cycle analyses. With continued investment in research and development, 3D printing could become a more viable and accepted method

of construction, transforming the way the industry is managed in remote, isolated, and expeditionary environments.

Introduction

Three-dimensional (3D) printed construction is an additive, layer-by-layer construction method that produces 3D objects from a digital file [45,46]. It is an interdisciplinary practice that incorporates materials science, architectural, structural, mechanical, and software engineering disciplines [47]. For 3D-printed construction to be considered a viable construction method in the long-term, it must be competitive with conventional methods and both useful to and usable by its end users [48,49].

This review focuses on 3D printing by material extrusion – specifically, contour crafting and concrete printing – because of the method's potential durability, reliability, and portability in remote environments [28,37,50]. Contour crafting uses layers of continuous ribbons of fresh concrete made from commercially available, standard industry, or *in situ* materials. It incorporates two trowels to shape and form the top and side of the layers as they are extruded to create smooth, accurate surfaces [51–60]. Similarly, concrete printing is also a wet extrusion method, in which pre-mixed concrete or cement-based mortar is deposited by a nozzle in layers to form a structure, without the use of formwork. However, it differs from contour crafting in that it does not incorporate surface finishing techniques, leaving the printed components with a distinctive layered appearance [37,48,57,61–66].

Currently, applications of 3D-printed construction are limited due to the small number of teams performing full-scale infrastructure design and construction [67]. Most studies only speculate on the applications of 3D-printed construction when it becomes a

more established technology. Popular applications include affordable, accessible housing, emergency shelter construction, and natural disaster relief [37,50,68–77]. Several studies suggest autonomous 3D-printed construction technology could also be revolutionary in remote or hazardous locations; areas with difficult terrain, unfavorable climates, or inhospitable environments; and in military locations for the erection and deployment of critical structures, forward base camps, and outposts [37,48,69,70,78–81]. However, while studies on 3D-printed construction often suggest the application of this technology in remote and underdeveloped areas, few studies analyze the feasibility of 3D printing in these environments.

This systematic review identified thirty review articles on the materials, methods, and applications of 3D-printed construction. Despite their significant contributions, none of these previous reviews focused on viability factors or applications in remote and isolated environments. Accordingly, this paper presents the results of a systematic review of the viability of 3D-printed construction. The goal of this review was to determine if 3D-printed construction is now, or could be, a viable replacement for conventional construction methods, particularly in remote environments. More specifically, the analysis identifies whether 3D-printed construction is reliable, cost-effective, and efficient compared to conventional construction. In this paper, remote environments are defined as locations characterized by geographic isolation, an underdeveloped economy, or hazardous conditions. Given the existing limitations of conventional construction in remote environments, these locations provide greater opportunity to leverage the benefits of 3D-printed construction than locations where conventional construction is already an established and prevalent method.

Methodology

This systematic review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines and was conducted using Elsevier's abstract and citation database, Scopus [22]. In this review, a total of 3,699 articles were discovered, and after applying pre-defined exclusion criteria, 238 articles were included (shown in supplemental files).

The search criteria for this review contained a set of seven terms on 3D printing, seven terms on engineering and construction, and twenty-eight viability-related terms, which were developed in conjunction with an earlier review based on trends observed in the literature [82]. Journal articles and conference papers with at least one 3D printing term, one engineering/construction term, and one viability term in their title, keywords, or abstract appeared in the search results. No words were excluded to ensure the maximum breadth of the search results.

The database search conducted on 4 June 2019 identified 3,699 documents. Forty-eight duplicate records were removed. The first screening reviewed paper titles and excluded 2,810 records in accordance with the exclusion criteria in Figure 3. The second screening focused on titles and abstracts and excluded an additional 499 records. In the final step, 342 full-text articles were assessed for eligibility. Seventy-four records and 30 review articles were excluded, leaving 238 publications for synthesis and inclusion in the final paper. Figure 3 depicts a flow diagram of the screening process.

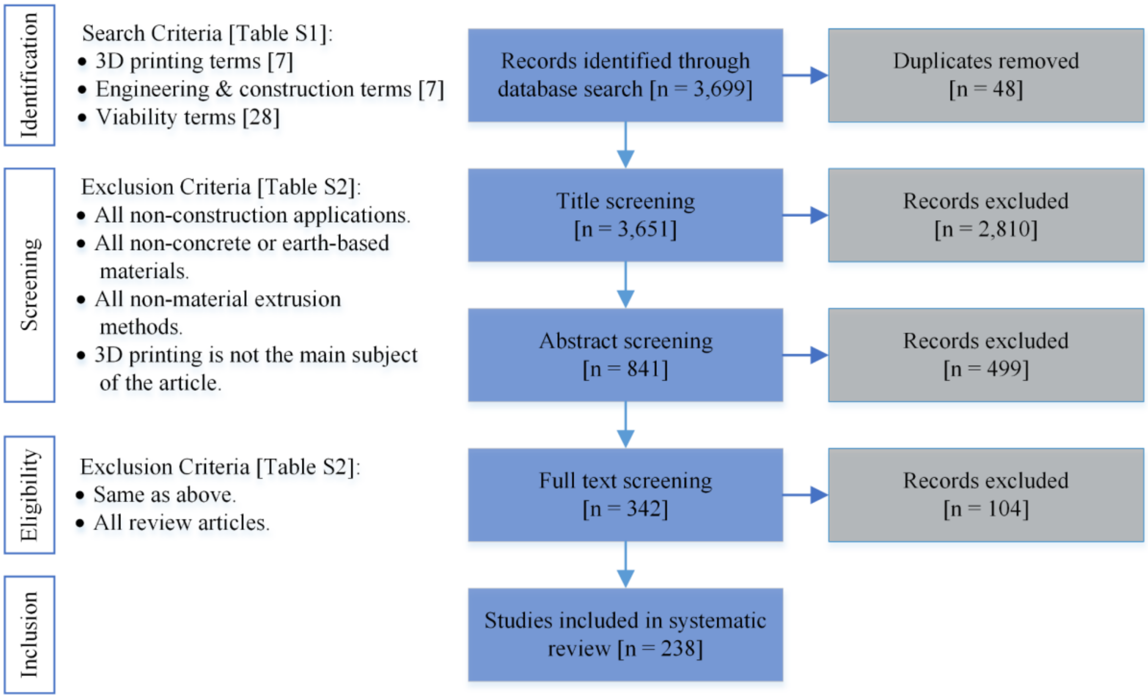

Figure 3. The PRISMA Flow Diagram for this systematic review summarizes how the search results were narrowed from 3,699 to 238 over three sequential screenings.

Characterization of Literature

This review of 3D-printed construction includes 238 publications spanning from January 1998 to June 2019. Each publication was classified into one of ten categories based on the primary focus of the paper: methodology, Earth applications, space applications, and the seven viability criteria – materials, structural design, efficiency, logistics, labor, environmental impact, and cost. Materials were the most common research focus, accounting for 41.2% of all publications selected for inclusion in this review. The next most common research focus was printing methodology, accounting for 19.7% of all publications, followed by space applications, which account for 11.8% of all publications. Five of the seven viability criteria – efficiency, labor, logistics, environmental impact, and cost – cumulatively comprise just 11% of the publications. While numerous publications focus on the potential benefits to construction time, labor,

logistics, environment, and cost, very few studies are dedicated to validating the benefits in each of these areas, as shown in Figure 4.

Figure 5 depicts the evolution of 3D-printed construction research subject matter from 1998 to 2018. This figure excludes 2019 because the review was conducted in June and therefore only includes half of the year's publications. While printing methodology has been a research focus since 1998, printing applications were not showcased in publications until 2005. Applications and materials did not become common research focuses until 2010. Research on 3D printing began a noticeable upward trend in 2015, with the body of literature steadily growing over the following years.

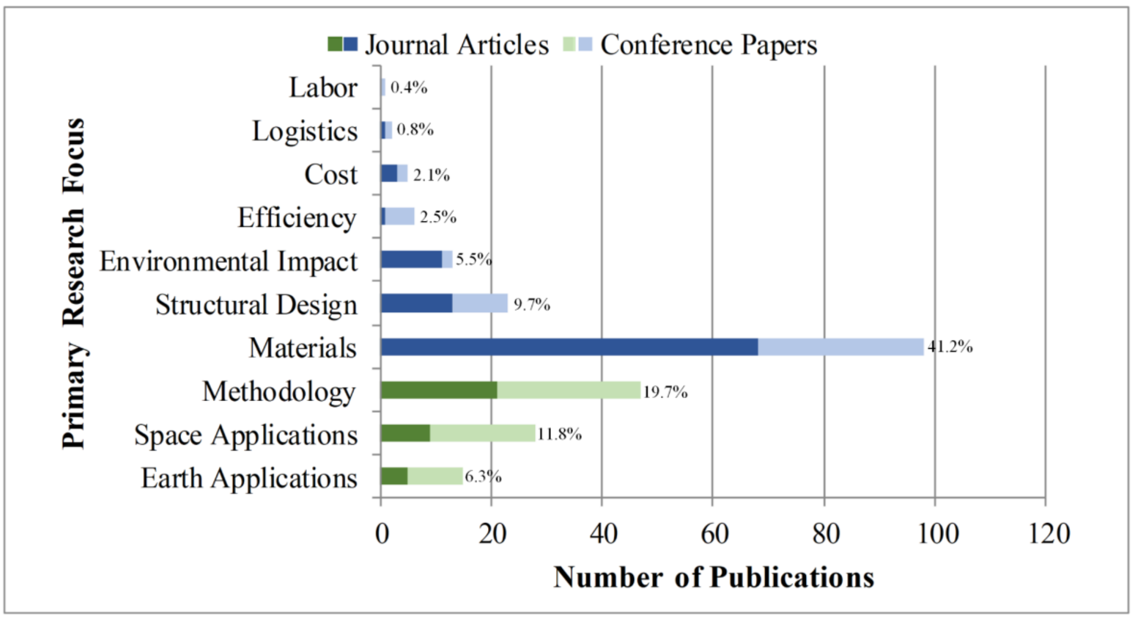

Figure 4. Number of 3D-printed construction publications by research focus and publication type. Viability criteria are represented in blue; printing methodology and applications are shown in green. The number at the end of each bar denotes the number of publications in the category as a percentage of total publications (n = 238).

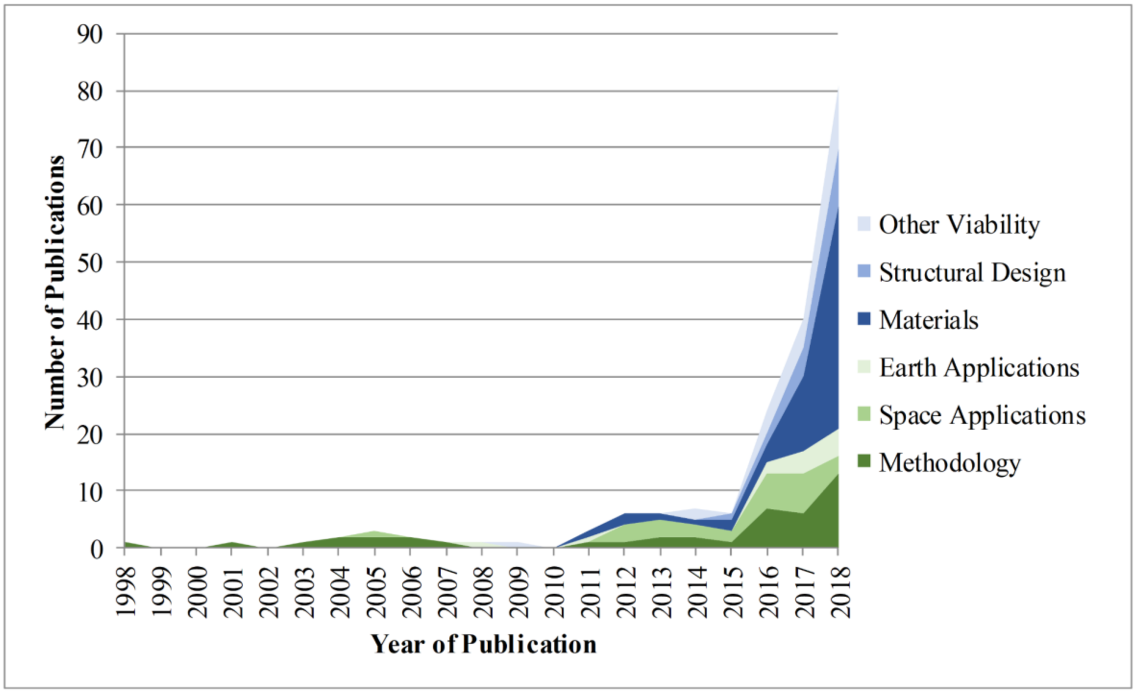

Figure 5. Graph highlighting the growth of 3D-printed construction publications over the review period. Viability criteria are represented in blue; printing methodology and applications are shown in green. "Other Viability" includes the categories of efficiency, labor, logistics, environmental impact, and cost, which cumulatively comprise 11% of all included publications.

Lastly, Table 3 identifies the most common journals and conferences in which publications on 3D-printed construction were found. Of the 238 publications included in this review, 45% were conference papers and 55% were journal articles.

Table 3. Most common 3D-printed construction journals and conferences.

# Pubs	Pub. Type	Journal or Conference Title
25	Journal	Construction and Building Materials
15	Journal	Automation in Construction
9	Journal	Materials
7	Journal	Cement and Concrete Composites
7	Journal	Virtual and Physical Prototyping
17	Conference	International Conference on Progress in Additive Manufacturing
17	Conference	International Symposium on Automation and Robotics in Construction
9	Conference	AIAA Space Conference and Exposition
8	Conference	MATEC Web of Conferences
7	Conference	Earth and Space
7	Conference	IOP Conference Series: Materials Science and Engineering

Evaluation and Discussion of Viability Factors

This review defines viability as the ability of 3D-printed construction to function successfully and be sustained in remote, isolated, or expeditionary environments where conventional construction capability may be limited. This review considers seven different aspects of viability: materials, structural design, process efficiency, labor, logistics, environmental impact, and cost. Each aspect of viability has a section that begins with an overview of the benefits of that factor, followed by a more detailed summary of the benefits, challenges, and considerations of each aspect that are relevant in remote environments. The discussion concludes with an investigation of three 3D-printed construction case studies specific to remote, isolated, and expeditionary environments.

Materials

Concrete is the most commonly used building material in the world because it is cheap, readily available, durable, strong in compression, fire-resistant, and able to be formed into almost any shape [30,83]. For these same reasons, concrete is also the most common material used in 3D-printed construction and is a natural choice for printing in remote environments [84,85]. However, the material properties and requirements of 3D-printable concrete differ from those of normal and self-compacting concrete, making active, reliable rheology control critical to the success of 3D printing applications [5,32,83,86–92]. Consequently, material compatibility is a significant factor determining whether or not 3D-printed construction technology will be adopted and implemented in remote environments [93,94]. The limited range of existing available, printable materials and the need for the development and standardization of new materials pose additional challenges to the adoption of 3D-printed construction, particularly in remote environments where material control is more difficult [5,42,45,54,77]. One study summarizes the material challenges well: "it seems that for each project… an individual composition of the printing mixture should be designed" [92].

The fresh properties of concrete are an important aspect of successful 3D-printed construction because they dictate the hardened properties [95–99]. A concern with concrete is its tendency to deform or even collapse in its fresh state [34]. Printed materials must demonstrate adequate fluid properties to be pumped and printed (pumpability and printability), while also displaying sufficient strength and solid properties to ensure they can maintain their shape without formwork (buildability), withstand self-weight throughout the printing process, and achieve the desired structural

performance [5,49,64,85,86,92,100,101]. Materials must be able to exhibit all of the aforementioned properties simultaneously to be viable in 3D-printed construction applications [47].

High-performance concrete can be challenging to print due to its rheological and stiffening properties [5,30,96,102–105]. Some researchers are examining the printability of alternative cement-based materials containing sulfur, limestone, fly ash, coarse aggregate, copper slag, and clay with the goal of expanding the range of viable, printable materials [98,106–110]. In general, additives and admixtures can improve the strength and control of rheological properties by improving either the process reactions – such as material setting and stiffening – or the material function [5,32,96,99,111–114]. However, additives and admixtures may be difficult to procure in remote environments, adding to the challenge of optimizing material rheology and performance.

Aggregate fineness, gradation, and grain size also influence material performance [115]. For example, increasing the amount of fine aggregate increases the yield stress, which in turn improves shape stability and shape retention [116]. The less sand or fine aggregate material has, the easier it is to extrude [117]. However, increasing the particle size can cause voids, weaker bonds, and lower yield stress [86]. The inability to control material quality and grade in a remote environment can pose challenges to 3D printing.

Structural Design

3D-printed construction has the potential to transform the way architects and engineers design buildings by permitting greater geometric complexity and freedom [32,37,42,67,76,105,118,119]. Increased structural complexity allows for the construction of hollow structures, which are capable of achieving the same strength as their solid

counterparts at a lower mass, and of structures optimized to meet weight, performance, and efficiency standards [32,118,120,121]. Additionally, 3D-printed construction is capable of the same strength as cast components and improved mechanical and thermal properties compared to conventional construction [45,120,122]. The use of building information modeling in conjunction with 3D-printed construction enables structural optimization: components are designed and printed based on the loads they are required to support rather than standardized for ease of design and construction, as is common in conventional construction [5]. While these potential benefits exist, this section highlights several structural challenges of 3D-printed construction, including optimizing structural performance, automating reinforcement, and operating under a lack of codes and standards.

Structural performance of 3D-printed construction is related to both printing parameters and overall print quality. Consequently, strict process control is required to ensure predictable, repeatable results [123]. Reliability and repeatability are particularly important in remote environments, when material, labor, and time constraints require guaranteed success on the first printing attempt. Parameters such as material properties, layer thickness, layer time, print path, print speed, pump speed, nozzle size, nozzle shape, and nozzle standoff distance all relate to print resolution, bond strength, and the ability of the printed structure to resist deformation [122,124–126]. As a result of this, several studies aim to optimize structural and material performance by creating models to control parameters such as material properties, print speed, structure geometry, and predicted strength and stiffness and relate them to the performance of the completed structure

[100,127–129]. These optimization models consider the parameters collectively, rather than designing for individual parameters [126].

The need for the automated placement of steel reinforcement to counteract concrete's weak tensile strength and improve its load-bearing capacity poses another challenge to structural performance [124,125,125,130–132]. While 3D-printed construction can be used in conjunction with conventional reinforcement methods, these methods can limit design freedom and restrict the benefits (namely labor and cost) automation brings to the construction industry [49,133]. Consequently, some current research has focused on alternative reinforcement options and multi-material printing technology such as post-tensioning reinforcement, fiber reinforcement, cable reinforcement, and steel extrusion reinforcement [49,67,124]. Furthermore, some studies have examined the possibility of automating rebar installation through the use of robotics [76].

The more fluid a mix is, the slower the set time, resulting in additional time between layers, longer total print time, and a reduction in interlayer bonding and structural strength [48]. Interlayer bonding ensures a printed component behaves as a homogeneous, monolithic structure free of flaws that can lead to stress concentrations [87,105,126,134–136]. Reducing the amount of time between layers helps to improve bonding and flexural strength by allowing layers to intermix, whereas increasing the time between layers allows for improved shape stability and reduced deformation [5,66,85,87,126,134,137–141]. Additionally, more time between layers causes increased void formation and porosity at the interface, two additional factors which adversely affect interlayer bonding [141,142]. Several additional factors impact interlayer bond strength,

including the layer thickness, nozzle standoff distance, surface contact area, and surface moisture content [66,87,126,143]. Each of these factors must be carefully monitored and controlled in remote environments to ensure adequate bonding and desired structural performance for a given application.

Another consideration of 3D-printed construction is the anisotropic and orthotropic behavior of printed components, in which each layer consists of bonded strips with little to no aggregate interlock [5,94,105,130,141,144,145]. The process results in laminated structures with weak joints, poor bonding between adjacent layers and beads due to minimal surface contact area, and reduced flexural strength [94,137,146]. Consequently, print direction has a noticeable impact on the load-bearing capacity of the structure – several studies found compressive strength and elastic modulus are both highest in the direction of the print path and are weaker in the other two directions [91,139,143], while other studies also noted that the loading resistance and mechanical properties varied depending on the loading direction [125,144,146].

Some studies question the reliability and safety of 3D-printed construction due to the difficulty of controlling and predicting printing parameters, mechanical properties, and structural performance [47,124]. This mentality is exacerbated by the lack of codes and standards regulating the 3D-printed construction industry [32,42,124,125,133]. Furthermore, tests that apply to conventional construction may or may not apply to 3D-printed construction [5,86]. The lack of codes and standards may not be an issue in some remote environments, where 3D-printed structures are more reliable and sound than existing makeshift structures. However, in other remote environments, such as military bases, adherence to codes and standards may be required. Using a hybrid 3D

print/conventional concrete approach to print permanent formwork out of concrete or polyurethane foam and fill it with conventional concrete has the potential to mitigate the limitations of both automated reinforcement and a lack of codes and standards governing 3D printing. This hybrid method enables formwork to be printed around conventional reinforcement framework and facilitates design to existing conventional codes [122,147–149]. This method also enables the use of fill materials that would otherwise not be compatible with 3D-printing [148].

Process Efficiency

The time constraints of a construction project often influence or even control decisions regarding scope, labor, and cost [42,48]. For this reason, one potential benefit of 3D-printed construction is the ability to construct higher-quality buildings in less time [32,76,77,135,150,151]. Unlike manual construction, automated construction is capable of printing continuously without requiring time off for the concrete to cure or the laborers to rest, which eliminates inactive time [28,76,77,84]. One study found that 3D-printed construction was nearly three times faster than building a 200m^2 house using traditional methods [76]. This shortened duration was primarily realized by eliminating formwork (estimate: three days to construct and remove) and reducing curing time (estimate: four or five days) [76]. 3D printing can also reduce design time by up to 60% and leverage Lean construction principles, including standardization of tasks and continuous process improvement, to refine the construction process and eliminate inefficiencies [4,76]. This rapid construction capability can be vital in remote environments where quickly meeting a housing need, responding to a natural disaster, or establishing a military base is required.

Optimizing print speed is a delicate balance: printing too quickly prohibits the development of early strength needed to support the structure's self-weight, while printing too slowly can lead to reduced bonding or even cold joints between layers [5]. Factors affecting print speed include the bead size, print precision, layer thickness [45], print path (including the use of angles versus curves) [76], material consistency [45], and rate of material deposit [122]. Given the many factors contributing to print speed, it is often not the best measure or comparison of process efficiency. For this reason, many studies prefer to provide data on print time. However, print time can be misleading because it only considers the time the printer is operating and actively extruding material [48]. Measures of elapsed time (total time worked on a print, including set-up, material preparation, print pauses, and cleanup) or construction time (total time from the start to the end of the print, to include time used by manual labor to place reinforcement, install doors and windows, and construct roofs) often provide a more accurate picture of the actual efficiency of 3D-printed construction technology [48].

One downside to efficiency of 3D-printed construction may be the lack of redundancy in the process and hardware: if the printer experiences any problems, construction must halt or switch to manual methods while troubleshooting occurs unless additional printers are available on-site [76]. In remote areas where spare parts or skilled maintainers are limited, this lack of redundancy could potentially delay the construction timeline. Additionally, because the amount of time concrete can remain in the pump and hose before solidifying is limited, print pauses and delays must be closely monitored [76].

Labor

One of the most apparent benefits of 3D-printed construction is increased process automation, which results in a reduction of construction manpower requirements and the potential for greater quality control [5,77,84,92]. Process automation has several positive and negative consequences, including decreased risk on the job site, mitigated labor shortages, reduced human errors, and increased interdependency between humans and machines. Process automation can be helpful in dangerous remote environments, such as active war zones or locations with nuclear fallout, but harmful in remote environments where the local economy is dependent on conventional construction jobs.

The construction industry is one of the most dangerous industries due to its high rates of fatality, injury, and illness [7,28,37]. The potential hazards on the job site include slips, trips, and falls; eye, skin, and respiratory tract irritation; silicosis; chemical burns; and overexertion [30]. Less dependence on labor reduces the risk of illness and injury and increases site safety by eliminating human exposure to potential hazards [4,28,77,81]. Given that remote environments can be inherently dangerous, the opportunity to limit the number of laborers exposed to hazardous conditions is valuable.

Automating the construction industry through 3D printing can also help mitigate labor shortages due to a lack of available skilled labor at remote locations [28,49,122]. Human errors account for more than 80% of total defects in housing construction and can be mitigated by an automated process, reducing the time and cost required for rework [152]. While one approach to 3D-printed construction is to create a fully automated or even autonomous process, the industry is still many years away from achieving this ideal. In the meantime, humans will need to work in tandem with 3D printers to complete select conventional construction tasks such as site supervision; material mixing and preparation;

installation of windows, doors, and roofs; and pre- and post-processing [28,37,77,78]. Ultimately, the benefits of construction automation will need to be weighed against the costs of shifting jobs away from construction and towards more material manufacture, particularly in areas dependent on the conventional construction industry to ensure socio-economic stability [78].

Logistics

3D-printed construction affords the opportunity to simplify construction logistics and management [26,28,72,77]. 3D-printed construction can shorten the supply chain by reducing lead times for materials and equipment and decreasing production times for the resultant components and structures [26,28]. This section highlights the opportunities 3D printing provides to minimize transportation logistics and special considerations for printing on-site versus off-site. Minimizing transportation logistics and supply chain delays is helpful in remote locations that may be difficult or dangerous to reach, such as remote mountain villages and frontline military bases.

Like conventional construction, 3D-printed construction aims to use locally sourced or *in situ* materials when available and accessible. Using local materials reduces or even eliminates material transportation logistics to remote, hard-to-reach locations and reduces the need to store and maintain extensive material inventories [42,50]. 3D-printed construction also reduces the number of laborers required to complete a job, which translates to simplified transportation logistics because fewer people must travel to the remote location and commute to and from the job site each day [76]. Similarly, because 3D printers eliminate the need for most conventional heavy equipment (unless printed components must be lifted and transported into place), less equipment needs to be

scheduled and transported to and from the job site [76,77]. Many construction-scale 3D printers are designed to be lightweight, portable, and easy to assemble, such as a version of a contour crafting machine that can break down into three main pieces to fit on a small flat-bed truck and a gantry-based printer system that can be deployed on a small cargo aircraft, enabling their use in remote environments [28,37,50].

Similarly to conventional construction methods, structures can be pre-printed (printed as modular components and assembled in place) or printed in place as a complete entity using a mobile printer [45,49,153,154]. If structures are printed as modular components, and subsequently moved into place, components will need to be designed to tolerate the stresses induced during lifting, transportation, and installation and avoid chips, cracks, or other damage in transit [26,122]. However, the advantages of this off-site approach include improved quality, production speed, and site safety [41]. On the other hand, printing components or structures on-site minimizes preparation tasks, transportation requirements, and installation steps [26,28,41]. It also eliminates the need to resolve damages on-site upon arrival and installation since everything is printed in place and can help with issues such as scalability, as printed components are often constrained by the volume of the printer [26,155,156]. However, on-site 3D printing, like conventional construction, is weather-dependent [28,41,77,92]. Weather-related challenges may be exacerbated in remote environments prone to dust storms and extreme weather phenomena.

Environmental Impact

The construction industry accounts for 40% of the world's material resource consumption, 40% of its energy consumption, 38% of its greenhouse gas emissions, and 40% of its solid waste generation [5,71,72,157]. In particular, concrete is responsible for 8% of the world's carbon dioxide emissions due to the energy-intensive process required to manufacture cement [30,124,158]. Consequently, the creation of affordable, sustainable, recyclable construction components is becoming an increasingly prevalent research focus [103,159]. 3D-printed construction has the potential to lower material consumption, energy use, emissions, and waste over the life cycle of the structure. Researchers estimate 3D-printed construction could reduce the environmental impact by up to 50% as compared to conventional construction [5,78]. This section addresses the ways 3D-printed construction can help mitigate each of these environmental challenges and minimize its footprint in remote locations.

The environmental impact of the printing process itself is negligible in comparison with the environmental impact of the materials manufacturing process [5,160,161]. The use of building information modeling enables material optimization by avoiding over-design and ensuring only the required concrete and reinforcement are utilized, while the application of 3D-printed construction makes these individual, optimized designs a reality [5,124,160,162]. Additionally, because 3D-printed construction is an additive process, utilizing only the amount of material required, it helps to reduce and eliminate overproduction and material waste from both the component and its formwork [37,42,45,76,77,84,119,152,161]. However, the downsides of eliminating formwork – sacrificed strength, stability, convenience, accuracy, and surface quality –

must be weighed against the environmental benefits [79]. One study indicates 3D-printed construction could reduce material consumption by as much as 40%, while another predicts it could reduce waste by up to 30% [28,161].

Another method to mitigate the environmental impact of construction materials is to transition from using highly industrialized materials known to have detrimental environmental impacts, and toward renewable materials, such as peat, geopolymers, and soil [95,112,139,157,160,163,164]. Earth construction is an alternative that utilizes a mix of locally sourced subsoil, water, and available fibers, such as straw [165,166]. While earth construction does not achieve the strength and durability of conventional, concrete-based construction, 3D-printed earth construction does have comparable structural and thermal properties to conventional earth construction and may be an appropriate solution in some remote areas where material quality and structural performance requirements are not as stringent [165,166]. However, extrusion speed, consistency, and continuity all pose challenges to the widespread application of 3D-printed earth construction [165]. Finally, recycled construction waste products, glass, mining tailings, organic materials, and other resources can also be used in concrete mixes to improve sustainability [32,77,84,119,124,152,167,168].

The printing process itself can lower localized environmental impact because printers are capable of being completely electric [54,71,72]. They can connect to the local power grid or run off generator power in remote locations. One study found the electricity demand during printer operations accounted for only 2% of the overall life cycle emissions and environmental impact of a 3D-printed wall [5]. 3D-printed construction also decreases the transportation impact, fuel consumption, and associated

emissions of construction by reducing or potentially eliminating the need for diesel-powered heavy construction equipment and commuting laborers on a job site [28,37,77,152]. Finally, 3D-printed construction is relatively quiet compared to conventional construction, reducing noise pollution [37].

Cost

Construction is a $3 trillion per year industry [75]. Consequently, one appeal of 3D-printed construction is its potential ability to cut total costs and increase the cost-effectiveness of several different aspects of construction [5,49,77,92,169]. For example, one study compared different methods of constructing a structural wall, and found 3D-printed construction was 10% to 25% cheaper than the cost of building with concrete masonry units, and 25% to 37% cheaper than the cost of cast-in-place construction [49]. These cost savings are important in low-income, underdeveloped, or post-disaster remote environments where economical methods of construction could transform communities. However, cost savings should be weighed against the benefits of job creation, especially given that in the aftermath of disasters, there is no shortage of labor supply. This section focuses on the financial impact of 3D-printed construction on four main components of the printing process: planning and design, materials, labor, and machinery [5].

One cost-benefit of 3D-printed construction is the elimination of the need for formwork [77,91,170]. Given that scaffolding, concrete molds, and their associated labor typically account for 35% to 60% of total construction cost, 3D-printed construction can generate substantial monetary savings [5,30,49]. Eliminating the need for formwork also reduces both materials and labor and cuts out a time-consuming step in the construction process [32]. Material costs can also be reduced by optimizing the design to avoid over-

engineering and reduce material waste; leveraging the use of locally sourced, *in situ*, or recycled resources; and minimizing the need for material transportation and storage [5,84,92,109,112,168,171]. However, material costs can escalate if admixtures are necessary to control the rheology and improve printability [5,107].

Labor can also be costly, comprising as much as 50% of a project's total cost [37,48]. While the labor costs of conventional construction are often higher than the material costs, in the case of 3D-printed construction, these proportions are reversed, so labor costs end up being less than half of the material costs [49]. Other cost benefits of labor include the reduction of overhead costs, as less supervision is required for 3D-printed construction than conventional construction, improvement in productivity, and reduction in number of errors [43,76].

The costs of construction planning and design are expected to decrease due to advancements in 3D modeling, building information modeling, and other technologies [5]. These benefits will increase in cases of large-scale implementation such as mass-produced housing or military barracks, in which the reusability of digital data could ultimately make planning costs negligible in comparison with conventional construction [5].

One cost unknown is that of the printer and supporting machinery, which varies based on the printing technique, material delivery system, and process precision [5,76]. Because large-scale printers are relatively new and scarce within the construction industry, they tend to have expensive up-front costs and unknown, ongoing maintenance costs. As 3D printing technology matures, costs are expected to fall as a result of industrial competition [32,77,172]. One study assumes the operating and maintenance

costs of a concrete printer equate to about $75 per hour [49]. However, the cost of using the technology is generally not accounted for in the calculation of total print costs, resulting in an underestimation of the cost of a printed structure or component [169].

Isolated Environment Case Study: Space Settlements

Space is a prime example of an isolated environment: it is geographically remote with no access to labor, equipment, and materials; it lacks an established construction industry or process; and it experiences harsh conditions including extreme temperatures, high radiation, dust storms, and moonquakes. However, the successful development of a 3D printing method for space could facilitate 3D printing on Earth – particularly the sustainable construction of housing [75,81,173–175]. Some materials proposed for use in space construction, such as basalt, sulfur, and recycled plastics and metals, are also available on Earth and may be more environmentally friendly than some existing construction materials [174,176]. Additionally, methods developed to extract and process materials in space may be harnessed on Earth to make greater use of *in situ* resources and mitigate existing issues with soil handling equipment, which have some of the highest maintenance costs and failure rates per operating hour among any industrial equipment [80,176].

The European Space Agency proposed establishing a lunar village as the next step in human space exploration, and human colonization of space is the goal by the end of the century as a way to mitigate Earth's diminishing resource supplies and increasingly frequent natural disasters [72,175,177]. 3D-printed construction can be used in space to create shelter and living quarters on the moon and Mars prior to human arrival to minimize human support requirements such as air, water, food, and transportation;

improve the safety of astronauts; reduce time to commission; and mitigate lunar dust interference [80,173,175,176,178–181]. Once the settlement is established in space, 3D printing may also be useful for maintaining the structures and facilitating structural repairs [181].

The use of 3D-printed construction in space offers several potential logistical advantages, such as eliminating the need to design constructed components to withstand launch forces and space travel and minimizing mass and volume on space launches [45,50,58,173,182]. Reducing the mass of materials, supplies, and equipment shipped from Earth by sourcing materials locally can save money on launch costs – one study estimates it could cost as much as $1 million per kilogram to transport material and supplies to Mars [69,175,183]. Several studies propose leveraging the abundant *in situ* material resources found on the moon and Mars, namely regolith, the crushed rock and dust produced on the moon's surface after centuries of micrometeorite strikes; basalt, an igneous rock formed during lava flow; and sulfur, a material particularly common in Mars that can be used as a fundamental ingredient or alternative binder in concrete [69,80,108,176–178,184].

3D-printed construction in space poses unique challenges, such as developing a printer that operates in microgravity and a vacuum-like environment with limited traction and producing pressurized structures that can provide substantial protection from radiation micrometeorite impacts, giving astronauts a space to live and work without being dependent on pressure suits [69,80,173,176,178,181,183]. However, some challenges encountered in space parallel challenges encountered when applying 3D-printed construction on Earth, such as developing a printer with built-in redundancy, the

capability to perform in extreme temperatures and dust storms, resistance to seismic loads, and the ability to operate and communicate autonomously over long distances without delays [80,173,176]. One unique benefit of in-space construction is that structural loads on the moon are only one-sixth of those on Earth, enabling the construction of slimmer structures requiring less time, materials, and energy [80].

Several studies point to contour crafting as a possible solution for in-space 3D-printed construction needs [56,69,72,80,175,179–181,183]. Another study proposed the All-Terrain Hex-Limbed Extra-Terrestrial Explorer robotic system, a large-scale, solar-powered printer capable of traversing irregular lunar or planetary surfaces and using a variety of print heads to stabilize surfaces and to produce walls, vaults, domes, shelters, hangars, berms, tunnels, paving, trench walls, landing and launch pads, modular panels, beams, and other components using *in situ* materials [69,180,183]. Additional approaches to in-space 3D-printed construction include the Archinaut, a platform created by a partnership between NASA and Made In Space, Inc., which combines both 3D printing and precision robotic assembly; and a method of extruding molten basaltic material into triangular panels, which can subsequently be used to construct domes for living, research, storage, communications, and other required functions [178,182]. Several simulations and proofs-of-concept are underway on Earth to develop and prepare 3D printing technology for use in the remote and isolated environments found in space, as shown in Figure 6 [74,75,174,185].

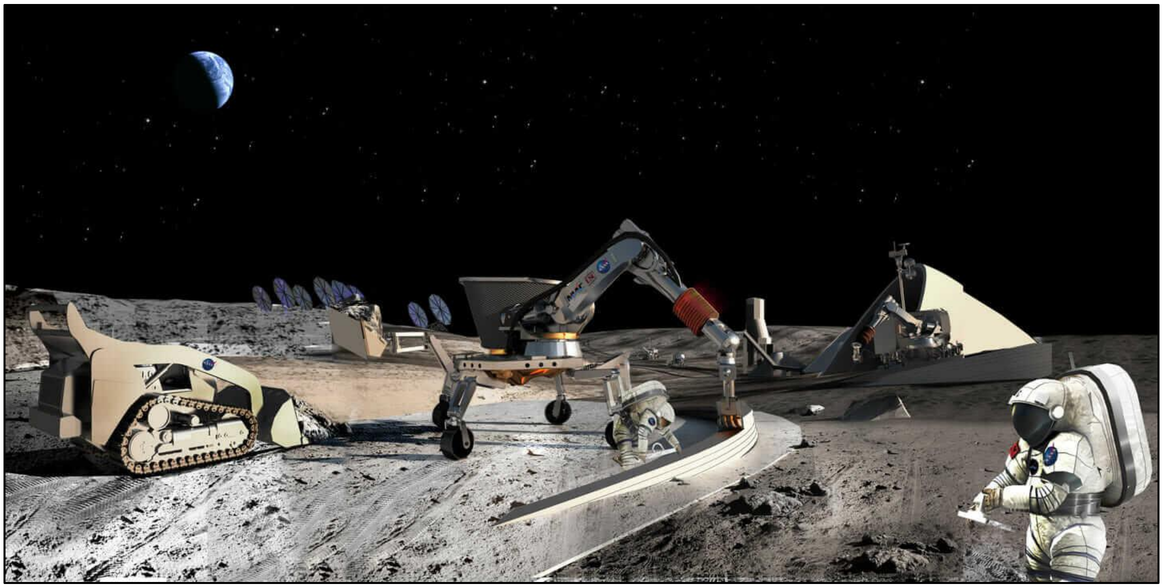

Figure 6. Rendering of potential uses for 3D-printed construction in space [186].

Remote Environment Case Study: Low-Income Housing

ICON, an Austin-based construction technologies company, developed a portable, gantry-style printer which uses a proprietary mortar mix to print its homes and structures [187]. ICON's first project was a 32.5m^2 (350ft^2) proof-of-concept home printed on-site in Austin, Texas, in March 2018 [187]. The home was permitted, built to International Building Code standards, and completed in approximately 47 hours of total printing time with the 3D-printed portion costing $10,000 [187]. This proof-of-concept established a foundation for greater technology and process development and for a partnership with a non-profit housing organization to build homes for the economically disadvantaged in Tabasco, Mexico, one of the most impoverished areas in the country. The goal of the partnership is to build a community of 50 single-family homes designed to withstand seismic activity by the end of 2020.

In late 2019, after 18 months of planning and refining its technologies, ICON completed construction of its first two printed homes, one of which is shown in Figure 7.

Despite challenges with unpredictable power, heavy rainfall, and localized flooding, each 46.5m^2, two-bedroom home was completed in a 24-hour print time spread across multiple days and finished by a local Mexican non-profit [188]. The 50 families selected to receive housing have a median monthly family income of $76.50 and were previously living in unsafe, makeshift shelters [188]. This application demonstrates the viability of 3D printing in the areas of structural design, process efficiency, labor, environmental impact, and cost. The greatest challenge to the viability of 3D-printed construction in this case study is the use – and associated transport – of a proprietary material that must be shipped to the printing location.

Figure 7. One of ICON's initial two homes 3D-printed in Tabasco, Mexico [187].

Expeditionary Environment Case Study: Military Construction

The United States Army Corps of Engineers Engineer Research and Development Center Construction Engineering Research Laboratory (ERDC-CERL) established the Automated Construction of Expeditionary Structures (ACES) program in 2015 to develop reliable, user-friendly 3D printing technology capable of generating custom-designed military expeditionary structures on demand, in the field, using locally available materials [15]. The goals of the ACES program include decreasing material usage; building stronger, more durable structures; minimizing manpower requirements; and reducing the

logistical and supply demands of construction. Currently, the program's focus is on the use of 3D-printed construction in expeditionary environments. The program utilizes a prototype gantry-style 3D printing system called ACES Lite that was designed and built under a cooperative research and development agreement between Caterpillar and ERDC-CERL. The printer was designed to be highly transportable, easy to assemble, and operable by minimum personnel.

Since May 2016, the ACES team has completed several prints, including a $3m^2$ military entry control point, two $48m^2$ concrete barracks huts (B-huts), a 10m 3D-printed concrete bridge, and a $7m^2$ military defensive fighting position. B-Hut 1 (Figure 8a) was the first full-scale, 3D-printed concrete building in the United States, while the bridge was the first 3D-printed bridge in the Americas and first of its kind to be printed in a field setting [16,189]. The focus during the printing of the second barracks hut was efficiency: B-Hut 2 (Figure 8b) was completed in 14 hours of print time (31.2 hours of elapsed time) spanning five days [17,190]. Each of these projects emphasized the printers' ability to employ locally sourced materials and operate in uncontrolled environmental conditions and have brought the U.S. military one step closer to having robust, deployable construction technologies.

(a) (b)

Figure 8. (a) B-Hut 1, a 48m^2 building printed in stages over the span of several weeks. (b) B-Hut 2, a 48m^2 chevron-style building printed in 14 hours over the span of five days.

Conclusion

Although 3D-printed construction is still in its infancy, there is potential for the future, as evidenced by the numerous applications, proofs-of-concept, and research advancements in the last decade. To determine whether or not 3D printing – or any other method of construction – is viable and preferred in remote environments, tradeoffs between several factors must be considered, including materials, structural design, process efficiency, logistics, labor, environmental impact, and cost. The factors are all interrelated, and rarely does a single construction method optimize all seven viability areas.

The case studies included in this review suggest that 3D-printed construction in remote environments is possible and is steadily improving in all seven viability factors assessed in this study. However, 3D-printed construction must overcome many challenges and obstacles pertaining to material rheology; structural integrity; process scalability; suitability to adverse environments; complete automation; unknown environmental impacts, and uncertain costs to be reliable, cost-effective, and efficient

enough to compete with conventional construction. These challenges are often exacerbated in remote, isolated, or expeditionary environments where access to materials, labor, and other resources are limited. Suggested areas of future research as they pertain to each of these challenges are as follows:

1. Material Rheology: Strong, reliable, printer-compatible materials are key to the successful implementation of 3D-printed construction technology [93,94]. Researchers should experiment with locally available or *in situ* materials found in expeditionary environments to ensure compatibility and effectiveness for printing. Additionally, caution should be taken before generalizing study results, as they may vary based on the specific chemical composition of a material mixture [191].
2. Structural Integrity: Further structural testing and definition of codes and standards are needed to ensure the structural integrity of 3D-printed components, particularly in areas prone to extreme weather, seismic activity, natural disasters, or military attack.
3. Process Scalability: Many studies are conducted using laboratory-scale printers in controlled conditions, rather than with construction-scale printers, in realistic environmental conditions. Scalability is a challenge because there are both physical and material constraints at larger scales [37]. Research must continue to move toward large-scale experimentation and building construction to ascertain the true capability of this technology and ensure its application to industry [172].
4. Suitability to Adverse Environments: Experimental conditions are highly simplified and may not reflect the performance of 3D printing in an actual construction site environment, which is exposed to inconsistent environmental

factors such as precipitation, temperature or humidity, dust and debris, and inconsistent lighting conditions. [192]. 3D-printed construction must be tested and demonstrated in uncontrolled environments to ensure the widespread effectiveness of this technology.

5. Complete Automation: Until methods are developed to automate the placement of reinforcement, utilities, windows, doors, roofs, and other building elements, labor demand can only be reduced – not eliminated. Research should continue to develop each of these methods to enable a fully autonomous process and ensure human safety in dangerous construction environments. However, an analysis of the tradeoffs between complete automation and human employment should also be conducted to fully understand and address the impacts of 3D printing on the construction industry.
6. Unknown Environmental Impacts: While many studies tout the potential environmental benefits of 3D-printed construction, others question whether or not these benefits are sufficient to justify its use. Because 3D-printed construction is a new, niche technology, experiencing its full benefit takes time: one study estimates that at best, only 5% of energy and emissions produced by overall industrial manufacturing and construction will be reduced by 2025 [78]. A formal life cycle analysis examining the sustainability impacts of the design, material preparation, construction, use, and eventual demolition of a structure is necessary to fully understand the environmental impacts of 3D-printed construction [42,161].

7. Uncertain Costs: Because 3D-printed construction is still such a new technology, little is known about its up-front, maintenance, and life cycle costs. Furthermore, different countries may experience different cost-benefits since the costs of planning and design, materials, labor, and machinery vary from country to country [76]. A formal cost-benefit analysis should be conducted for different cases (e.g. location, printing method, printing technology, and desired output) to gain a complete understanding of how the cost of 3D-printed construction compares to that of conventional construction [4].

With continued investment in research and development, 3D printing could become a viable and accepted method of construction with the potential to transform the way the industry manages materials, design, scheduling, labor, logistics, sustainability, and cost in remote, isolated, and expeditionary environments. However, as 3D-printed construction continues to mature and become more competitive, decision-makers will need to consider the tradeoffs between conventional and 3D-printed construction methods and the anticipated consequences of their decision on the local society and economy.

IV. The Benefits and Challenges of On-Site 3D-Printed Construction: A Case Study

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Abstract

In 2018, U.S. Marines, Navy, Air Force, and Army Corps personnel demonstrated the capability of 3D-printed construction in an expeditionary environment at Camp Pendleton, California. The tri-service exercise culminated in the construction of a 10-meter concrete bridge – the first of its kind to be both printed and placed in a field environment. In this exercise, the 3D printer was transported from Champaign, Illinois to Camp Pendleton, where a team of Marines assembled it close to where the bridge would be placed. The Marines performed initial beam and pier design; the Army Corps completed the structural design, steel reinforcement, and coding. The concrete ingredients were measured and mixed using a volumetric mixer and skid steer. After mixing, the concrete was pumped through a hose to the printer nozzle. Each beam was printed sequentially; the piers were printed concurrently. Reinforcement and forklift pockets were laid manually during pauses between print layers. As printing progressed, the finished members were covered and allowed to cure for two to five days before placement. Despite challenges with weather, materials, hardware, and power, the U.S. military successfully demonstrated the potential of 3D-printed construction in the expeditionary environment by proving it is possible to print and place a bridge on-site using locally sourced materials. The U.S. military also exhibited the potential of 3D

printing to reduce the labor, materials, and logistics required for military construction. Furthermore, the exercise revealed additional, future opportunities to automate the 3D printing process and lessen the manpower demand.

Introduction

In December 2018, U.S. Marines from the 7th Engineering Support Battalion (7th ESB), Navy Seabees from Naval Mobile Construction Battalion FIVE (NMCB 5), an Air Force officer from the Air Force Institute of Technology, and researchers from the Army Engineer Research and Development Center - Construction Engineering Research Laboratory (ERDC-CERL) demonstrated the capability of three-dimensional (3D) printed construction in an expeditionary environment at Marine Corps Base Camp Pendleton, California. The demonstration was part of Exercise Steel Knight, a Marine-led exercise spanning the western United States that focused on military skills, tactics, and capabilities utilized in the expeditionary environment. The exercise's 3D-printing component had three primary goals: to train the 7th ESB in the printer assembly and construction process; to integrate NMCB 5's volumetric mixer, the "CreteMobile," into the material preparation process; and to construct the first 3D-printed bridge in a field setting in the Americas. Furthermore, the bridge was designed to support a team of Marines crossing in full gear shortly after placement. While this proof-of-concept was the first time four branches of the military collaborated on a single 3D printing effort, it is one of a series of advancements to military 3D printing efforts achieved by ERDC-CERL in recent years.

3D Printing

3D printing is an advanced additive manufacturing process capable of producing a range of complex structures and components without formwork using a layer-by-layer

material deposition approach [6–8]. Charles Hull developed the first 3D printer in 1986 using stereolithography; soon after, the manufacturing sector adopted the technique [8,25]. 3D printing was not applied to the building and construction industry until 1997, when Joseph Pegna made the first attempt at cement-based additive manufacturing [193]. The following year, Behrokh Khoshnevis, a professor at the University of Southern California, invented the contour crafting method, which uses a trowel to create smooth and accurate edges and surfaces [194]. Currently, over thirty groups are researching and developing 3D-printed construction technology around the world [24].

While still in the early stages of research and development, 3D-printed construction has the potential to outperform conventional construction due to its ability to lower total costs, decrease labor requirements, eliminate the need for formwork, reduce material utilization, shorten construction duration, increase customization, and enhance sustainability [4,6,8,10,11]. In addition to these benefits, 3D-printed construction is capable of greater strength than its conventionally cast counterparts and, thanks to the elimination of formwork, can be used in more complex structural applications [24,25].

ACES Program History

ERDC-CERL established the Automated Construction of Expeditionary Structures (ACES) program in 2015 to develop the capability to print custom-designed expeditionary structures in the field, on demand, using locally available materials [15]. The goals of the ACES program include minimizing manpower requirements, decreasing material usage, reducing the logistical demand and supply train in the expeditionary environment, and building stronger, more durable structures. In 2017, the ACES team printed a 4.9m x 9.75m x 2.4m (16ft x 32ft x 8ft) concrete building in Champaign,

Illinois: the first full-scale, 3D-printed concrete building in the United States [16]. This was quickly followed by the first military demonstration of 3D-printed concrete with the U.S. Marine Wing Support Squadron 372 (MWSS 372), which produced unique wall sections for testing utilizing the 3D printer known as ACES Lite (Figure 9). ACES Lite is a prototype deployable 3D printing system designed and built under a cooperative research and development agreement between Caterpillar and ERDC-CERL. The printer was designed to be highly transportable, easy to assemble, and operable by minimum personnel. It is currently ERDC-CERL's most efficient and highly utilized printer.

Figure 9. ACES Lite Assembled On-Site at Camp Pendleton, CA.

Due to its transportability, ACES Lite is involved in many on-site and off-site demonstrations. In April 2018, the ACES Lite team helped train Army personnel at the Maneuver Support, Sustainment, Protection, Integration Experiment at Fort Leonard Wood, Missouri during the first field-tested, 3D-printed concrete experiment in the world. In August 2018, the team collaborated with Marines from the 7th ESB and MWSS 372 to continuously print a second building in Champaign [17]. After the success of the

completed structure, the 7th ESB requested a demonstration of 3D printing capabilities at Camp Pendleton as part of Exercise Steel Knight to create a 3D-printed concrete bridge.

Materials and Methods

The 3D printing process can be broken into four main steps: printer transportation and assembly; structural design and programming; material preparation; and printing, curing, and placement.

Transportation & Assembly

Currently, only four ACES printers have been developed and tested, and all are based at ERDC-CERL in Champaign. In order to transport ACES Lite to Camp Pendleton, the printer was disassembled, organized, and packed for the first time ever into a 6m x 2.1m x 3m (20ft x 7ft x 10ft) shipping container by a team of four people in two hours. Supplies and supporting equipment, such as toolboxes, a power washer, and a tent to protect the computer from the elements were also packed into the shipping container. The container was subsequently loaded onto a semi-truck, where it began its 3-day, 3,250km (2020mi) journey across the U.S.

Upon arrival at Camp Pendleton, a team of seven Marines, previously untrained on the equipment or setup, assembled the printer in 58 minutes under the supervision and instruction of the ERDC-CERL personnel. The frame required 21 minutes to assemble, the bridge required 4 minutes, the ballasts required 10 minutes, and the remaining components of the printer (e.g. hose, nozzle, etc.) required 23 minutes. The printer assembly process is facilitated by lightweight, labeled components; simple connections; the requirement for only simple tools; and the opportunity to assemble some sections, such as the bridge, on the ground before lifting them into place. After the demonstration

was complete, the printer was disassembled and packed into the same shipping container in 25 minutes for its return trip to Champaign.

Structural Design & Programming

The temporary bridge structure was comprised of beams and piers. The initial beam and pier design was conducted by the Marines and modeled using AutoCAD before being sent to ERDC-CERL for determination of reinforcement locations and conversion to Linux computer numerical control (CNC) G-code. The bridge was designed to span a 9.75m (32ft) dry culvert located 0.2km (0.1mi) from the print site on Camp Pendleton. It consisted of three 3.35m (11ft) long beams and two 2.1m (7ft) tall piers with 2.1m x 0.91m (7ft x 3ft) bases. Each beam is a Double-T type beam consisting of one 0.91m (3ft) wide, 0.1m (0.33ft) deep flange and two 0.36m (1.2ft) wide, 0.25m (0.83ft) deep webs (Figure 10). The concrete mix incorporated polyolefin monofilament fibers for increased toughness and resistance to temperature changes and shrinkage. The flange was reinforced with weld wire fabric; the beams were constructed with top and bottom steel reinforcing bars. Since the design was intended to be temporary, the piers were only designed to take vertical compression loads. Therefore, in this instance, the pier was only reinforced every five layers with reinforcing mesh and relied primarily on the concrete to take the temporary loads.

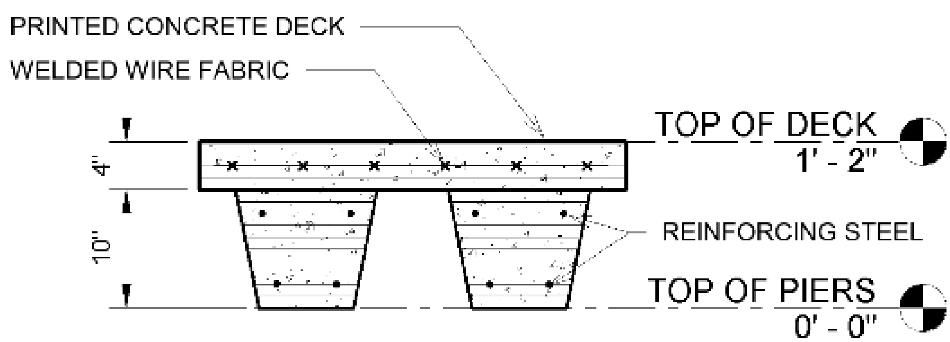


Figure 10. Beam Cross-Section.

Prior to printing, the printer was manually leveled and calibrated by moving the nozzle to one corner of the frame, which acted as a reference point from which the rest of the printer could be leveled. While the print path was pre-programmed into the computer, the print speed and pump flow rate were both adjusted manually using a CNC controller and variable frequency drive (VFD) pump controller, respectively. Due to variation in concrete batches, both the print speed and pump flow rate required adjustments to attempt to maintain a constant rate of material deposition.

Material Preparation

The concrete mix used for the print was comprised of cement, fine aggregate, coarse aggregate, short polyolefin monofilament fibers, water, and rheology-controlling admixtures. In past printing demonstrations by ERDC-CERL and the 7th ESB, concrete was measured and mixed manually in small batches [49,190]. Although these demonstrations proved that 3D printing could be expedient and cost-effective in comparison to conventional construction methods, the material measurement process was time-consuming, labor-intensive, and impractical for the expeditionary environment. In an effort to better simulate the methods and equipment available on military deployments, Exercise Steel Knight leveraged the use of the Navy Seabees' CreteMobile, a volumetric mixer manufactured by Brothers. After manually loading each ingredient into its respective hopper within the CreteMobile, the mixer was calibrated to ensure accurate mix proportions.

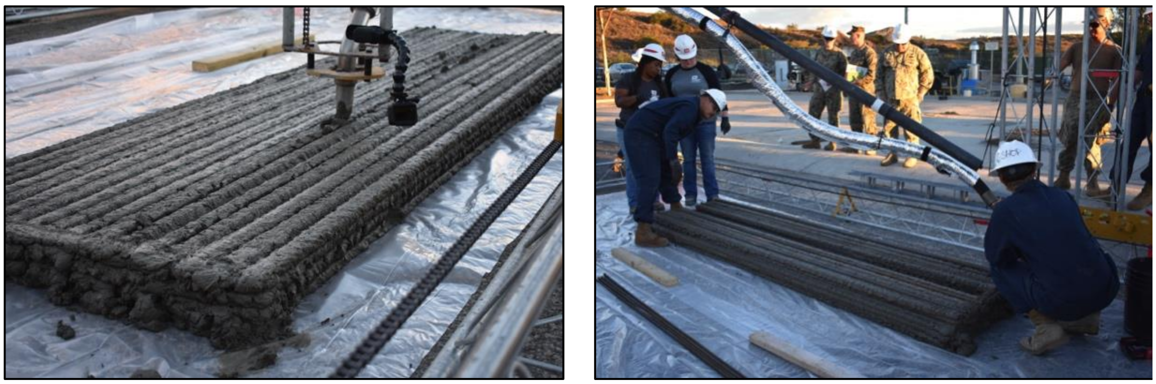
Once fully calibrated, the CreteMobile produced a test batch of concrete. Concerns quickly arose regarding the effect of the previous days' rain on the CreteMobile's ability to mix the batches accurately. After repeated test batches, visual

inspection of the prepared concrete determined that the mixture produced by this method could not be utilized due to the moisture content of the fine aggregate. Rain had left the sand wet, causing it to clump and preventing the CreteMobile from precisely dispensing the required proportion of fine aggregate. An additional Cementech mixer located on-site experienced the same issues. The decision was made to use the CreteMobile to efficiently measure out the required proportions of other ingredients (cement, coarse aggregate, and fibers) and dispense them into a small concrete batch mixer attached to a skid steer. The fine aggregate and water were measured manually and added to the skid steer attachment for mixing. Once mixed, each batch was transferred to the concrete pump with VFD modification for immediate use by the printer and vibrated by a Navy Seabee to liquefy the mixture, reduce internal friction, eliminate the air voids, and push the concrete through the pump.

Printing, Curing, & Placement

After assembly, programming, calibration, and material preparation were complete, printing began. A plastic tarp was laid down on the print surface to prevent the printed concrete from adhering to the existing pavement. The beams were printed first due to their simpler design, followed by the piers. On 7 December, Beams 1 and 2 were printed; beams 3 and 4 were completed on 8 December. Each beam was printed sequentially; a fourth beam was printed in the event that one of the other three beams was damaged during transportation and on-site placement. Given the design of the bridge, each beam was printed upside-down: the bridge deck was printed first (Figure 11a), while the two girders supporting the deck and transferring force to the piers were printed afterward. ACES Lite does not yet have the capability to automate the placement of

reinforcement; therefore, the computer operator followed construction plans with detailed layer-by-layer reinforcement instructions and manually paused the print to allow for the insertion of rebar or wire mesh reinforcement (Figure 11b). Rebar loops were placed using the same method to facilitate the beams' transportation to their final location. At the conclusion of printing, all of the beams were covered with plastic tarps and allowed to cure. Beams 1 and 2 cured for five days; beams 3 and 4 cured for four days.



(a) (b)

Figure 11. (a) Printing beam 1; (b) placing rebar on beam 1.

Printing of the two piers began on 8 December and continued through 10 December. Due to their height and number of layers, the piers were printed concurrently; however, each printed as a separate program. Consequently, after printing several layers of one pier, the print was paused and the nozzle was manually calibrated to pick up where printing left off on the other pier – this pattern continued until the completion of the two piers. As with the bridge beams, steel reinforcement was manually placed into the piers at the appropriate points in the print. However, due to the size and dimensions of the piers, each pier was also constructed with both rebar loops and two forklift pockets to facilitate transportation. These pockets were not programmed into the design; therefore, after a certain layer height was reached, the pocket locations were marked, printed concrete was

removed by hand, and coated foam molds were placed to create voids in the finished components. Due to the size of the piers and the need to print both concurrently, the piers required multiple days to complete. When printing stopped for the night, the print surface of each pier was texturized to minimize the adverse effects of cold joints and promote bonding between the hardened and fresh concrete when the print resumed. The completed piers were covered with wet textiles and cured for two days.

With the exception of the ends of each bridge beam, which were hand-trowelled to facilitate a smooth connection between beams; and the edges of both piers, which were hand-trowelled to ensure proper material compaction and prevent collapse, the surfaces of the components were not finished. This was done in order to highlight the 3D-printed nature and layered appearance of the completed bridge.

On 12 December, the completed bridge components were lifted onto a flatbed truck using a 7-ton crane, transported from the print site to the dry culvert, and placed in their final location by crane. The two piers were placed first, followed by the outer bridge beams and finally the center bridge beam. The fourth bridge beam printed in the event of damage was not required. The entire placement process took three hours, and the completed bridge supported twenty people simultaneously.

Results and Discussion

Ultimately, Exercise Steel Knight achieved all three of the Marines' objectives: to train the 7th ESB, utilize the CreteMobile (albeit in a modified capacity), and construct a bridge. The Camp Pendleton bridge is the first 3D-printed bridge in North America and the first 3D-printed bridge in the world to be printed in a field environment. While the

proof-of-concept was successful, several challenges encountered over the course of the demonstration provide opportunities to improve the technology and process.

Weather

Shortly after completing the printer assembly and site set-up, Camp Pendleton experienced inclement weather, necessitating the cancellation of 1.5 days of printing. As a result of this lost time, the bridge was completed later than expected and other planned elements of the exercise had to be cancelled. Additionally, the heavy rain altered the moisture content of the fine aggregate, which resulted in subsequent material issues as discussed in section 2.3. Inability to control the weather is one of the biggest challenges and unknowns of on-site or near-site 3D printing and will need to be accounted for in future 3D printing developments.

Hose & Nozzle Clogging

As a general rule of thumb, coarse aggregate diameter should not exceed one-third of the diameter of the nozzle in order to reduce the chances of clogging. The aggregates delivered to the site had a high level of variation from the initial sampling of aggregates, including dissimilar materials delivered by the same supplier between loads, which led to complexities associated with variations in the mix. The varying aggregate size (often exceeding 1cm (0.4in) in a 3.2cm (1.25in) nozzle), coupled with the addition of polyolefin monofilament fibers, caused clogs in the hose and nozzle. Each time the team encountered a clog that could not be eliminated by placing more concrete in the pump (and therefore more pressure in the hose), the hose had to be disassembled into sections and flushed out with water and a foam ball. If flushing was not immediately possible, the hose was pounded with sledgehammers to prevent the concrete from setting

prematurely in the hose. If the flushing process took more than a few minutes to complete, the concrete left in the pump often stiffened to the point that it had to be shoveled out and replaced with a fresh batch.

In an effort to reduce the frequency of clogging, the 3.2cm (1.25in) nozzle (Figure 12a) was removed and replaced with a new, 5.1cm (2in) nozzle (Figure 12c) to allow for a larger filament size and smoother flow. In the interim between nozzles, there was a brief period of time in which the component was printed without any nozzle (Figure 12b), resulting in lower print resolution and less control over the material flow. Once the new nozzle was attached, the team found it did reduce the instances of clogging in the printing process. Figure 12 depicts the effect of each nozzle on the print filament.

(a) (b) (c)

Figure 12. (a) Original 3.2cm nozzle; (b) no nozzle; (c) new 5.1cm nozzle.

The clogging issues can be mitigated in future prints by modifying the G-code to reduce delays; controlling the concentration of fibers; using less large aggregate or reducing the size of the small aggregate; employing a larger and more powerful pump, hose, and nozzle (which would decrease the amount of time needed to print a component, while also reducing the print resolution); adding a "purge point" to the hose (so the hose sections do not need to be removed and separated in order to flush out stiff concrete); and having additional spare hoses and nozzles on hand (to expedite the flushing process in the event that a clog does occur).

Generator Failure

In order to simulate the conditions experienced on military deployment, in lieu of traditional power, a multi-outfitted generator supplied power to the 3D printer. A Marine power production technician was assigned to monitor and maintain the printer for the duration of the print. Despite this precaution, on 9 December, the generator failed in the early afternoon, midway through printing the two piers. Without the generator, the print was paused with concrete suspended in the pump, hose, and nozzle, unable to be cleared until power was restored. The team again used sledgehammers to pound the hose and prevent the concrete from setting.

It took approximately 45 minutes for the Marine technician to get the generator back online. Once it was back online, the hose and nozzle were both flushed out, the concrete in the pump had to be disposed of and replaced with a fresh batch, and the computer had to be manually recalibrated to recognize where the print path left off. The interruptions in printing and ultimate generator failure were attributed to unidentified power surges and a need to service the generator.

Material Collapse

Despite the popularity of concrete in 3D-printed construction, research on its printed properties is limited and designs constructed of different materials under varying conditions still need to be assessed for overall material and structural quality [30,34]. Prior to starting the exercise, the team lead acknowledged that materials are the biggest risk and unknown of the 3D printing process because of uncertain and varying material quality and performance. The team did not encounter any material collapse issues while constructing the four beams; however, collapse under self-weight did become an issue

while printing the piers, which were substantially larger, taller, and had more layers. In order to allow sufficient time for early strength to develop to support subsequent layers, only 7-10 consecutive layers could be printed at a time before pausing the print to work on the other pier. Even with this practice in place, at several points, wet concrete sheared off of the sides of the pier as a result of inconsistent concrete flow from layer to layer near the edges of the pier, as seen in Figure 13. Communication challenges between the CNC controller and VFD pump controller also led to material collapse: at one point, the print path was paused to resolve an issue, but the pump continued to transport concrete through the hose to the nozzle, resulting in the rapid deposit of excess material to one edge of the pier and a subsequent collapse. Each time a small section of the pier collapsed; it was manually repaired before continuing the print.

Figure 13. Material Collapse Under Self-Weight.

The possibility of material collapse can be reduced by implementing best practices for print design, limiting the number of consecutive layers printed at a time, printing tall components concurrently to increase initial curing time and early strength, designing the geometry of the print to be self-stable under its own weight, troweling the surface and edges of the component during printing, incorporating accelerators into the

concrete mix, and synchronizing the VFD and CNC controls to avoid miscommunication between individuals.

Labor Considerations

As construction becomes increasingly automated, the quantity of laborers needed – and the associated number of injuries and hazards incurred – is expected to decrease, helping to eliminate risk and reduce the costs associated with both the labor itself and the potential injury or fatality [6,7,28]. However, the current printing process used in Exercise Steel Knight is still fairly labor-intensive. It required a small team of individuals to prepare and mix the concrete (a minimum of two: one to measure the ingredients and one to operate the skid steer), one individual to vibrate the concrete, one individual to monitor and control the pump flow rate, and one individual to monitor and control the print speed using the computer. These individuals also placed the reinforcement and manually repaired the piers as needed during pauses between print layers. During tasks such as initial set-up, end of day clean-up, and flushing out the clogged hose, it was helpful to have additional laborers on hand to expedite the work.

As development and testing of ACES Lite continues, these tasks will become increasingly automated, reducing the manpower required on the print site. Replacing the current concrete pump with a self-vibrating model, synchronizing the VFD and CNC controls with the main computer, automating the placement of reinforcement, and utilizing trowels to finish the print surface (as the ERDC-CERL team did on the first full-scale 3D-printed concrete building in the U.S.) could reduce the printing labor requirement by up to 40%.

Conclusions

Despite challenges with weather, materials, hardware, and power, the U.S. military successfully demonstrated the potential of 3D-printed construction in the expeditionary environment by proving it is possible to print and place a bridge on-site using locally sourced materials, resulting in the first 3D-printed bridge in the world to be printed in a field environment in 12 hours of total print time (Figure 14). Additionally, the exercise accomplished the two additional Marine goals of training their personnel and incorporating the Seabees' volumetric mixer into their printing efforts and achieved continued progress towards CERL's overarching goals of reducing the manpower, materials, and logistics required for construction. Furthermore, the exercise revealed additional, future opportunities to automate the 3D printing process and lessen the manpower demand by upgrading the pump, synchronizing the VFD and CNC controls with the main computer, developing methods of automating the placement of reinforcement, and streamlining the set-up and clean-up process through continuous printing operations.

Figure 14. Completed Bridge.

An in-depth analysis of time, labor, and material requirements is necessary to determine whether the current state of development of 3D-printed construction outperforms conventional construction in the field environment. However, this proof-of-concept is evidence that 3D printing in the military expeditionary environment is possible and holds great potential, and developments are on track for it to become a standard element of military construction in the future.

V. The Viability and Simplicity of 3D-Printed Construction: A Case Study

Abstract

In November 2019, U.S. Marines, Air Force, and Army Corps of Engineers personnel demonstrated the viability and simplicity of 3D-printed construction in a controlled environment at the U.S. Army Engineer Research and Development Center – Construction Engineering Research Laboratory in Champaign, Illinois. The tri-service exercise spanned three days and culminated in the construction of three 1m x 1m x 1m (3ft x 3ft x 3ft) concrete dragon's teeth (square pyramid military fortifications used to defend against tanks and armored vehicles) and several custom-designed objects. The structural components were printed using a custom-built, gantry-style printer called ACES Lite 2 and a commercially available, proprietary mortar mix. This paper examines the viability of using 3D-printed construction in remote, isolated, and expeditionary environments by considering the benefits and challenges associated with the printing materials, structural design, process efficiency, labor demands, logistical considerations, environmental impact, and project cost. Based on the results of this exercise, 3D-printed construction was found to be faster, safer, less labor-intensive, and more structurally efficient than conventional construction methods: the dragon's teeth were printed in an average of 57 minutes each and required only two laborers. However, the use of commercially procured, pre-mixed materials introduced additional cost, logistical burden, and adverse environmental impact as compared to traditional, on-site concrete mixing and production. Finally, this paper suggests future applications and areas of further research for 3D-printed construction.

Introduction

In November 2019, U.S. Marines from the 7th Engineering Support Battalion (7th ESB), an Air Force officer from the Air Force Institute of Technology, and researchers from the Army Engineer Research and Development Center - Construction Engineering Research Laboratory (ERDC-CERL) demonstrated the viability and simplicity of three-dimensional (3D) printed construction in a controlled environment at ERDC-CERL in Champaign, Illinois. The demonstration was part of Exercise Burgeon Strike, a tri-service exercise with one primary objective: to show how easy 3D-printed construction can be. Specifically, the exercise aimed to prove that 3D-printed design and construction can be taught to anyone, accomplished with only two laborers, and used in a range of diverse applications. Exercise Burgeon Strike is one of a series of advancements to military 3D printing efforts achieved by ERDC-CERL in recent years.

3D-Printed Construction

3D-printed construction is an advanced, additive construction process capable of producing a variety of complex structures and components without formwork using a layer-by-layer material deposition approach. The process combines elements of materials science with architectural, structural, mechanical, civil, and software engineering to print full-scale structures and components [47]. Three of the most common methods of 3D-printed construction are contour crafting, a wet extrusion method that uses two trowels to shape the top and side of the material layers as they are being extruded; concrete printing, a wet extrusion method used to print both the perimeter and infill of structures without incorporating trowels for surface finishing; and powder bed fusion, a dry method that uses a binder, laser, or electron beam to fuse powdered material together [45,55,66].

These methods are typically used to either print the structure itself or to print molds and formwork subsequently filled with conventional concrete [47].

For 3D-printed construction to be recognized as a viable construction method, it must be competitive with established conventional methods [190]. While still in the early stages of research and development, 3D-printed construction has the potential to become a disruptive technology and outperform conventional construction by reducing material utilization, enabling greater structural complexity, shortening construction duration, decreasing labor demand, simplifying construction logistics, enhancing sustainability, and lowering costs.

ACES Program History

ERDC-CERL established the Automated Construction of Expeditionary Structures (ACES) program in 2015 to develop reliable, user-friendly 3D printing technology capable of generating custom-designed military expeditionary structures on demand, in the field, using locally available materials [15]. The goals of the ACES program include decreasing material usage; building stronger, more durable structures; minimizing manpower requirements; and reducing the logistical and supply demands of construction. Given the limited commercial availability of construction-scale 3D printers and the ACES program's desire to produce rugged, robust printers capable of withstanding conditions found on military deployments, ERDC-CERL opted to develop or co-develop all six of its 3D printers in-house. The first printer, ACES 1, had a print area of 1m x 1m x 1m (3ft x 3ft x 3ft) and was used primarily to test printing materials and reinforcement methods; while the most recent printers, ACES Lite 1 and 2, boast approximate print areas of 6m x 3m x 3m (20ft x 10ft x 10ft) and 12m x 6m x 3m (40ft x

20ft x 10ft), respectively, and have successfully been used to construct full-scale buildings and bridges.

In May 2016, the ACES team completed its first large print – a military 1.8m x 1.8m x 2.4m (6ft x 6ft x 8ft) entry control point, shown in Figure 15a – introducing the possibilities for 3D-printed construction. In August 2017, the ACES team printed a 9.75m x 4.9m x 2.4m (32ft x 16ft x 8ft) concrete barracks hut (B-hut) in Champaign, Illinois – the first full-scale, 3D-printed concrete building in the United States – followed by the design, printing, and structural testing of six unique wall sections [16]. The subsequent year, in August 2018, the team collaborated with Marines from the 7th ESB and Marine Wing Support Squadron 372 to continuously print a second concrete B-hut in Champaign, shown in Figure 15b [17]. The reinforced, chevron-style building was completed in 14 hours of print time (31.2 hours of elapsed time) spanning five days [190]. B-hut 2 was quickly followed by the construction of a 10m (33ft) 3D-printed concrete pedestrian bridge, the first 3D-printed bridge in the Americas and the first bridge to be printed in a field setting [189]. Most recently, in August 2019, the ACES team again partnered with the 7th ESB to construct a 4m x 2m x 2.5m (14ft x 7ft x 8ft) military defensive fighting position (DFP), shown in Figure 15c. The DFP was printed using a 7.6cm (3in) nozzle and Blastcrete pump, demonstrating the ACES program's "big, fat, and fast" printing capability. Each of these prints emphasized the printers' ability to employ locally sourced materials and operate in uncontrolled environmental conditions. For Exercise Burgeon Strike, the focus shifted from simulating the printers' use in an expeditionary environment to establishing how simple 3D-printed construction can be when factors such as materials and environment are controlled.

Figure 15. (a) Entry control point; (b) Barracks Hut 2; (c) Defensive Fighting Position.

Materials and Methods

Exercise Burgeon Strike consisted of two primary components: a crash course in G-code and a demonstration of controlled printing capabilities. This section highlights the materials and methods associated with each.

Designing with G-Code

The first day of the exercise was dedicated to an introduction to writing Linux computer numerical control (CNC) G-code. While four of the eight Marine and Air Force personnel in attendance had prior experience with the 3D-printed construction process, none of the personnel had ever written G-code. After defining commonly used terminology, a selection of which are highlighted in Table 4, the class worked its way through four progressive coding examples: a square, a hexagon, a truss cross-section, and an irregularly shaped design that included varying angles and curves. In less than three hours, the tutorial was complete, and personnel were given the freedom to create their own designs, to be printed two days later.

Table 4. Sample of Commonly Used G-Code Terminology.

Terminology	Command	Comment
M03	Tool On; Forward	Turns pump on – integrates computer with pump.
G01	Linear Interpolation	Moves nozzle in a straight line to specified coordinates.
G02	Circular Interpolation	Moves nozzle clockwise on a given radius to specified coordinates.
M02	End of Program	Turns pump off; indicates the end of code.

Design for the dragon's teeth (Figure 16) was completed by the ACES team prior to the start of the exercise using CAMotics, an open-source G-code simulator for 3-axis CNC [195]. Each dragon's tooth was comprised of 48 layers: odd layers were printed in a clockwise spiral from the outside edge of the tooth to the center, while even layers were printed in a counterclockwise spiral from the center to the outside edge to eliminate the need to stop material flow and relocate the nozzle between layers. The first 24 layers created a solid base, while the remaining 24 layers contained a hollow rectangular prism for manually placed rebar and sand fill. Each dragon's tooth was printed in one continuous printing session.

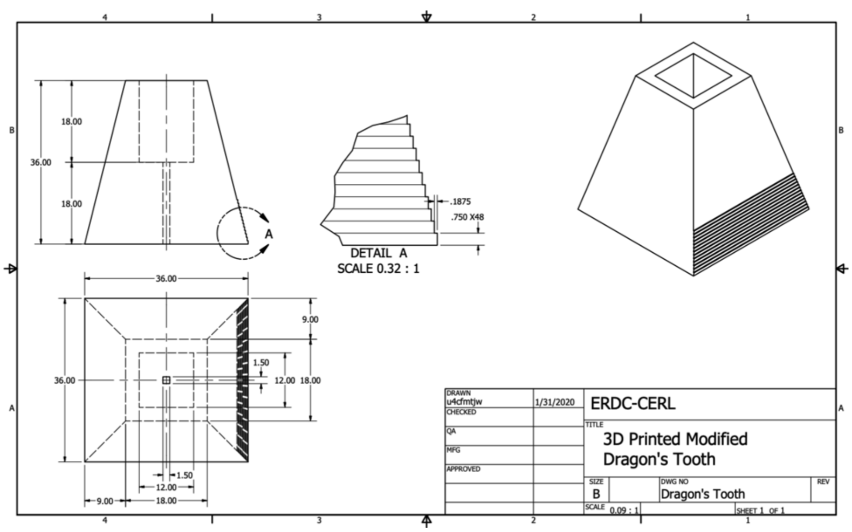


Figure 16. Design for Dragon's Teeth.

Preparing Materials

To demonstrate the simplicity of 3D-printed construction, in lieu of using locally sourced materials, which are subject to varying chemical composition, environmental conditions, and batching – causing inconsistent and unpredictable material performance – a commercially procured mortar mix manufactured by Gulf Concrete Technology was used. The mix is a single component Portland cement-based plaster with a proprietary blend of admixtures and fine aggregate that requires only the addition of water [196]. It is 4,000 psi, medium-set, and can be sprayed, printed, or hand-troweled [196]. The mix also has the benefits of high adhesion, constant durability, a smooth finish, and resistance to cracking [196].

The materials were mixed and delivered to the printer using the m-tec duo mix 2000 pump, which has a standard delivery volume of 22L/min, a conveying distance of up to 60m, and a conveying height of up to 30m [197]. The ACES team outfitted the pump with a variable frequency drive (VFD) to enable both manual and CNC modes. Prior to printing, the pump was primed with water and tested to visually and tangibly ensure even, dough-like material consistency. Given the small size (1.35m x 0.64m x 1.39m; or 4.4ft x 2.1ft x 4.6ft) of the pump, its capacity is limited to four bags of material, and it is not equipped to handle large aggregate.

Printing with ACES Lite 2

ACES Lite 2 is a prototype deployable 3D printing system designed and built under a cooperative research and development agreement between Caterpillar and ERDC-CERL. The printer is highly transportable (able to be packed in a 6m x 2.1m x 3m [20ft x 7ft x 10ft] shipping container), easy to assemble (able to be assembled and

disassembled by a trained team of four people in 30min; all pieces can be lifted into place by three or fewer people), and operable by as few as two personnel. Because ACES Lite 2 is based at Champaign, it was already in place and assembled at the start of Exercise Burgeon Strike.

Prior to printing, the printer was leveled and calibrated by moving the nozzle to a relative origin. While the print path and pump start/stop commands were pre-programmed into the computer, the print speed and pump flow rate were both adjusted manually using a CNC controller and VFD controller, respectively. Thanks to the consistent batching and material performance, the need for these manual adjustments was minimal.

After leveling, calibration, and material preparation were complete, printing began. All of the components were printed on reusable plastic forklift pallets sprayed with WD-40 to facilitate their relocation upon completion. The three dragon's teeth were printed first (Figure 17) to allow them additional time to cure; all three were completed on 6 November. On 7 November, two concrete masonry units and several other custom designs were printed during a half-day print session. That afternoon, the three dragon's teeth and one of the custom designs, the Marines 7th ESB logo, were transported by forklift to a nearby location for a group photo before returning to the printing laboratory to finish curing in a controlled, protected environment. None of the printed surfaces were finished in an effort to highlight the 3D-printed nature and layered appearance of the completed components.

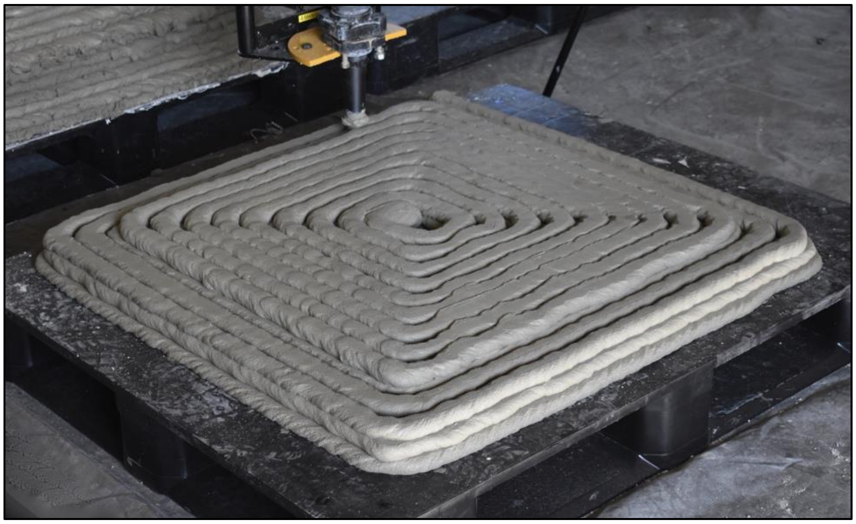


Figure 17. Printing Dragon's Tooth 2.

Results and Discussion

This section examines the viability of using 3D-printed construction in a remote, isolated, or expeditionary environment by considering the benefits and challenges associated with the printing materials, structural design, process efficiency, labor demands, logistical considerations, environmental impact, and project cost as compared to conventional construction.

Materials

3D-printed construction is far more sensitive to material rheology than conventional construction methods due to the need to ensure good pumpability, printability, buildability, and open time [47]. Consequently, in past ACES prints using locally sourced materials mixed on-site, material performance was consistently the biggest challenge faced in the printing process [189]. In contrast, the material mix used in this print was commercially produced, ensuring consistent, predictable material properties batch-to-batch. Additionally, the m-tec duo mix 2000 pump measured and added water to the mix, eliminating the potential for human error in the process and

ensuring consistent material fluidity throughout printing. These qualities make bagged material mixes a simpler and more reliable alternative to batch mixing concrete on-site using locally procured materials or ordering a ready-mix concrete delivery. With the exception of a pause to mix more materials and three brief breaks in material extrusion while the first dragon's tooth was being printed, material extrusion was constant and issue-free throughout the two days of printing.

The downside of using a bagged material mix for 3D printing is that it could be difficult, expensive, or time-consuming to procure in a remote, isolated, or expeditionary environment, depending on the location. The benefits of more consistent material performance must be weighed against the cost and logistics tradeoffs. The downside of using the m-tec duo mix 2000 pump is that it cannot handle large aggregate, which limits the pump's compatibility with different materials and its value in aggregate-dependent applications.

Structural Design

One advantage of 3D-printed construction over conventional construction is the elimination of the need for formwork, which in turn reduces material consumption, construction time, labor demand, environmental impact of materials, and cost [146]. The lack of dependence on formwork facilitates the design and construction of more complex structures, such as the square pyramid base and hollow rectangular core found in the dragon's teeth [32]. The ability to easily print a hollow core or center also introduces opportunities for hybrid 3D-printed/conventional construction methods: for example, the ACES team reduced total print time and material cost by printing a hollow core in each dragon's tooth and subsequently filling the core with sand. The core could have also been

filled with conventional concrete, which does not have to achieve the same strict material standards as 3D-printed concrete. If the dragon's teeth were constructed conventionally, they would have likely been designed as solid components to simplify construction.

The downside of 3D-printed construction is the lack of codes and standards regulating the industry – existing design and construction standards are not applicable to 3D printing methods [133]. However, the importance of codes and standards tends to diminish in remote, isolated, or expeditionary environments due to the need to build structures as expediently as possible, so this is likely not a serious concern. Finally, when it comes to building reinforced structures, 3D-printed and conventional construction are comparable because both require manual placement of reinforcement.

Process Efficiency

A second advantage of 3D-printed construction over conventional construction is the ability of the printer to print continuously, with only limited time off for cleaning and maintenance [198]. Each dragon's tooth was printed in an average of 57 minutes, with an average of 60 minutes elapsed time per dragon's tooth. These averages do not include the time required for set-up, pump calibration, material testing, printer calibration, cleanup, or curing. The medium-set material supported its self-weight during continuous printing operations and solidified after approximately 45 minutes. As a result, the finished components were able to be transported within 48 hours of printing.

If the dragon's teeth were constructed conventionally, each tooth would require approximately 2.75-6 labor-hours to build, depending on whether the teeth were constructed over several days (able to reuse formwork once the components cured) or simultaneously (each requiring their own formwork). This estimate assumes 5 labor-

hours to design, measure, cut, and construct formwork and 1 labor-hour to prepare and place each small batch of concrete [199]. Like the time estimate for 3D-printed construction, these estimates do not include the time required for set-up, pump calibration, material testing, printer calibration, cleanup, or curing.

The downside of 3D-printed construction is it is more susceptible to changes in environmental conditions than conventional construction. For example, it is difficult to extrude and place concrete in wet conditions, whereas wood framework or other conventional construction methods may be able to continue in rainy weather.

Labor Demand

A third significant advantage of 3D-printed construction over conventional construction is increased automation, which translates to a reduction in construction labor demand [198]. During Exercise Burgeon Strike, only two personnel were required at any given time to maintain printing operations: one laborer monitored the computer and made minor manual adjustments to print speed and pump speed as needed, while the other monitored the pump and added additional bags of pre-mixed material when required.

If the dragon's teeth were constructed conventionally, the two laborers' roles would have looked very different. Instead of simply monitoring the printer and pump operations, the individuals would have been responsible for measuring and building the formwork, coating the formwork with an anti-stick material for easy removal at the completion of the print, measuring the concrete ingredients, batch mixing the concrete, placing the concrete into the forms, and ensuring the concrete was covered and kept moist during curing. For larger components and structures, more than two laborers would

have been required to ensure a safe and successful build, whereas, with 3D-printing, only two are needed, regardless of the print size.

The downside of increasing automation in the construction process is that reduced labor demand can be detrimental in areas dependent on construction jobs to ensure socio-economic stability [78]. However, in remote, isolated, or expeditionary environments where the goal is to build structures as expediently as possible, increased automation will not adversely impact jobs and can be beneficial because it improves safety in unfavorable environments [92].

Logistical Considerations

Another benefit of 3D-printed construction over conventional construction is the opportunity to simplify construction logistics and management by shortening the supply chain [32]. 3D-printed construction replaces countless tools and pieces of heavy equipment with a single printer and pump capable of being transported anywhere in the world in a standard-size shipping container. By automating the construction process, it reduces the need to transport and house personnel in remote, isolated, or expeditionary environments, which also reduces the associated food, fuel, and energy needs. If locally sourced concrete and materials are used, material transport costs and logistics become negligible.

The downside of using a bagged material mix for 3D printing is that it negates many of the logistical benefits of 3D-printed construction. The material used in this exercise must be shipped from its manufacturing location in Long Beach, Mississippi to the printing location, which adds mass and consumes valuable cargo volume on aircraft,

trucks, or ships used for transport. Shipping materials also requires additional coordination, time, and manpower.

Environmental Impact

An additional benefit of 3D-printed construction over conventional construction is the opportunity to minimize negative environmental impacts caused by material waste, energy consumption, and greenhouse gas emissions [5]. Because 3D printing is an additive process, it uses only materials required for the structure and eliminates the need for material formwork, thereby eliminating material waste. ACES Lite 2 is an electric printer and can run on generator power in remote, isolated, or expeditionary environments without established electrical networks, thereby reducing energy consumption as compared to conventional construction, which typically relies on diesel-powered heavy equipment. Finally, when 3D-printed construction leverages locally sourced or recycled materials – which have much lower emissions than processed or refined materials created by a material manufacturing process – and eliminates the need for material transport, it lowers greenhouse gas emissions associated with construction.

The downside of using a bagged material mix for 3D printing is that it negates some of the environmental benefits of 3D-printed construction: namely, the opportunity to reduce emissions by using less industrialized materials [160]. Compared to locally sourced materials, the bagged material mix is energy-intensive to both prepare and transport.

Cost

A final meaningful advantage of 3D-printed construction over conventional construction is decreased total cost as a result of material savings, structural design

improvements, increased process efficiency, reduced labor demand, simplified logistics, and improved sustainability [5]. Each dragon's tooth had an estimated cost of $750 as detailed in Table 5. If the dragon's teeth were constructed conventionally, each tooth would have had an estimated cost of $500, as detailed in Table 6. Both 3D-printed and conventionally constructed dragon's teeth use the same reinforcement, so rebar costs were excluded from the calculations to highlight cost differences between the two methods.

Table 5. Cost Breakdown of Dragon's Tooth Using 3D-Printed Construction.

Category	Cost	Notes
Labor	$81.67	2 laborers x $39.15/hr [199] x 1hr x 1.043 inflation factor [200]
Printer	$75.00	Estimated cost of printer operations and maintenance: $75/hr [49] x 1hr
Materials	$592.30	30 bags of material (conservative estimate) x $16.41/bag + $100 shipping

Table 6. Cost Breakdown of Dragon's Tooth Using Conventional Construction.

Category	Cost	Notes
Labor	$273.79	(1 carp x $49.25/hr + 1 lab x $39.15/hr) [199] x 3hr x 1.043 inflation factor [200]
Formwork	$119.78	36SFCA x $3.19/SFCA [199] x 1.043 inflation factor [200]
Concrete	$103.63	18CF x $5.52/CF [199] x 1.043 inflation factor [200]

In this case study, the downside of using a bagged material mix for 3D printing is that it is over three times more expensive than conventional concrete mixed using locally sourced or *in situ* materials. However, the cost of labor of 3D-printed construction is less than a third of that of conventional construction. If more affordable materials are used in future applications, the cost of 3D-printed construction could be competitive with conventional construction methods.

Conclusions

During Exercise Burgeon Strike, the U.S. military successfully demonstrated how easy and accessible 3D-printed construction could be through its rapid construction of three concrete dragon's teeth, shown in Figure 18. The exercise validated all three of the ACES program's claims:

1. 3D-printed construction design can be taught to anyone. – Eight personnel with no prior knowledge of G-code were equipped to design their own simple components after just three hours of training.
2. 3D-printed construction accomplished with only two laborers. – The dragon's teeth were printed with one laborer monitoring the computer and another laborer monitoring the pump.
3. 3D-printed construction can be used in a range of diverse applications. – 3D-printed construction has been demonstrated in applications ranging in size from CMUs to $48m^2$ ($512\ ft^2$) structures. It has been used for practical applications, such as housing, gap-crossing, and base defense; and for novelty applications, such as custom logos and architectural features.

Figure 18. Tri-Service Team with Completed Dragon's Teeth and 7th ESB Logo.

Based on the results of this exercise, 3D-printed construction was found to be faster, safer, less labor-intensive, and more structurally efficient than conventional construction methods. However, the use of commercially procured, pre-mixed materials introduced additional cost, logistical burden, and adverse environmental impact as compared to traditional, on-site concrete mixing and production. These findings are specific to this application and case study: because there is substantial variability in materials, printers, and structural design, other 3D printing case studies may not reach the same conclusions when compared to conventional construction.

One limitation of this exercise is the fact that it was conducted in a controlled environment using controlled materials – two unrealistic conditions for an assessment of viability in remote, isolated, or expeditionary environments. Controlled environments may be present in remote 3D printing scenarios if the printer is set up inside a shelter and used to print small components or components requiring greater environmental and process control. These components can be printed within the shelter and placed in their final destination once cured. Controlled materials may be valuable in remote 3D printing scenarios when used in hybrid 3D-printed/conventional construction. For example, commercially procured, bagged materials can be used to quickly and efficiently print structural formwork, which can then be filled with conventional concrete. This hybrid use facilitates material performance during 3D-printed construction, while also being cheaper and less logistically demanding than printing the entire structure using bagged materials.

VI. Conclusions and Recommendations

Research Conclusions

In an effort to provide an understanding of the potential viability of 3D-printed construction in the expeditionary environment, this thesis aimed to address two primary research objectives:

1. Systematically review the available literature to identify the primary viability considerations affecting 3D-printed construction, compare the benefits and challenges of 3D-printed construction versus conventional construction, and establish a framework to guide future research and development.
2. Analyze two recent case studies of military 3D-printed construction to identify specific lessons learned and future viability considerations.

The first objective was accomplished in Chapters 2 and 3. In “A Review of Reviews: Assessing the Viability of 3D-Printed Construction,” seven primary viability considerations were identified: materials, structural design, efficiency, labor, logistics, environmental impact, and cost. Each of these viability considerations are highly interrelated – a change one aspect of viability can positively or negatively affect each of the remaining six aspects. For this reason, viability must be optimized to determine which construction method is most appropriate for a given application. In “A Systematic Review of the Viability of 3D-Printed Construction,” the benefits and challenges of 3D-printed construction versus conventional construction were compared. The top benefit and challenge of each viability consideration as they pertain to the expeditionary environment are highlighted in Table 7.

Table 7. Summary of Top Viability Benefits and Challenges.

Viability Factor	Benefit	Challenge
Materials	Cheap & readily available	Controlling rheology
Structural Design	Optimized performance	Automating reinforcement
Process Efficiency	Faster construction times	Establishing redundancy
Labor	Increased safety	Creating an autonomous printing process
Logistics	Shortened supply chain	Combatting weather and environmental conditions
Environmental Impact	Reduced emissions	Eliminating use of highly industrialized materials
Cost	More affordable construction	Dealing with unknowns

The second objective was accomplished in Chapters 4 and 5. Chapter 4, "The Benefits and Challenges of On-Site 3D-Printed Construction: A Case Study," demonstrated that while 3D-printed construction is possible in a field environment, lack of material reliability and consistency is the greatest challenge to the implementation of 3D printing in expeditionary environments. In contrast, Chapter 5, The Viability and Simplicity of 3D-Printed Construction: A Case Study," showed how easy 3D-printed construction can be when highly controlled materials are used. However, achieving greater control of rheological properties comes with tradeoffs, namely in the areas of cost, logistics, and environmental impact. Again, viability must be optimized in order to maximize benefit and minimize undesirable costs and affects associated with different construction methods for a given application.

Research Significance

In the last four years, research into 3D-printed construction has grown exponentially. While several researchers suggest potential applications of the technology to emergency shelter construction, post-disaster relief and recovery, construction in

remote or inhospitable environments, establishment of military bases, and autonomous space construction, very few studies focus on practically determining the feasibility of using 3D-printed construction in these applications. Instead, the vast majority of existing research investigates materials and applications in an ideal, controlled environment and fails to address how viable this technology is in a remote, uncontrolled environment. This thesis is the first to identify the critical viability factors that must be considered when selecting and implementing a construction method, discuss these factors as found in existing literature, and apply these factors to 3D printing case studies.

Research Contributions

This research produced one of the first systematic reviews of 3D-printed construction, and the first review of 3D-printed construction in remote or expeditionary environments. This review provided a systematic, replicable methodology for filtering 3D printing conference papers and journal articles. Additionally, this thesis generated two case studies of 3D-printed construction, both of which highlight recent innovations and accomplishments in the field while also providing a detailed run-down of challenges and advantages encountered during printing. These case studies laid the groundwork for collaborative, tri-service 3D printing efforts with the Army and Marine Corps, as seen in both Exercise Steel Knight (Chapter 4) and Exercise Burgeon Strike (Chapter 5).

This thesis was the first dedicated study and analysis of 3D-printed construction conducted by the U.S. Air Force. The findings could help shape future Department of Defense 3D-printed construction research and testing, as well as the Air Force's decision to invest in and implement this technology. This research culminated in the development

of two journal articles, three conference papers, one book chapter, and two poster presentations.

Recommendations for Future Research

The seven challenges identified in Table 7 should be a top research focus going forward to facilitate future widespread implementation of 3D-printed construction. Additional areas of future research are as follows:

1. Material Rheology: Strong, reliable, printer-compatible materials are key to the successful implementation of 3D-printed construction technology. Researchers should experiment with locally available or *in situ* materials found in expeditionary environments to ensure their compatibility and effectiveness for printing.
2. Structural Integrity: Further structural testing and development of codes and standards is needed to ensure the structural integrity of 3D-printed components, particularly in areas prone to extreme weather, natural disasters, or military attack. Future research should also consider applications of hybrid conventional/3D-printed construction.
3. Process Scalability: Research must continue to move toward large-scale experimentation and building construction to ascertain the true capability of this technology and ensure its application to the expeditionary environment.
4. Suitability to Adverse Environments: Experimental conditions are highly simplified and may not reflect the performance of 3D printing in an actual expeditionary environment, which may experience weather, inconsistent environmental factors such as temperature or humidity, and dust. 3D-printed

construction must be tested and demonstrated in uncontrolled environments to ensure the widespread effectiveness of this technology.

5. Complete Automation: Until methods are developed to automate the placement of reinforcement, utilities, windows, doors, roofs, and other building elements, labor demand can only be reduced – not eliminated. Research must continue to develop each of these methods to enable a fully autonomous process and ensure human safety in dangerous construction environments.
6. Unknown Environmental Impacts: A formal life cycle analysis examining the sustainability impacts of the design, material preparation, construction, use, and eventual demolition of a structure is necessary to fully understand the environmental impacts of 3D-printed construction.
7. Uncertain Costs: A formal cost-benefit analysis should be conducted for different cases (e.g. location, printing method, printing technology, and desired output) to gain a complete understanding of how the cost of 3D-printed construction compares to that of conventional construction.

In addition to the above areas of future research, the following military-specific questions should also be addressed:

1. What are some possible uses and applications of 3D-printed construction for each branch of the military?
2. Which AFSC(s) or MOS(s) are best equipped to assume the responsibilities and tasks associated with 3D printing? What core competencies will these career fields be expected to fulfill in regards to 3D printing?
3. How can 3D printing be integrated into military engineering operations?

Appendix

List of Presentations:

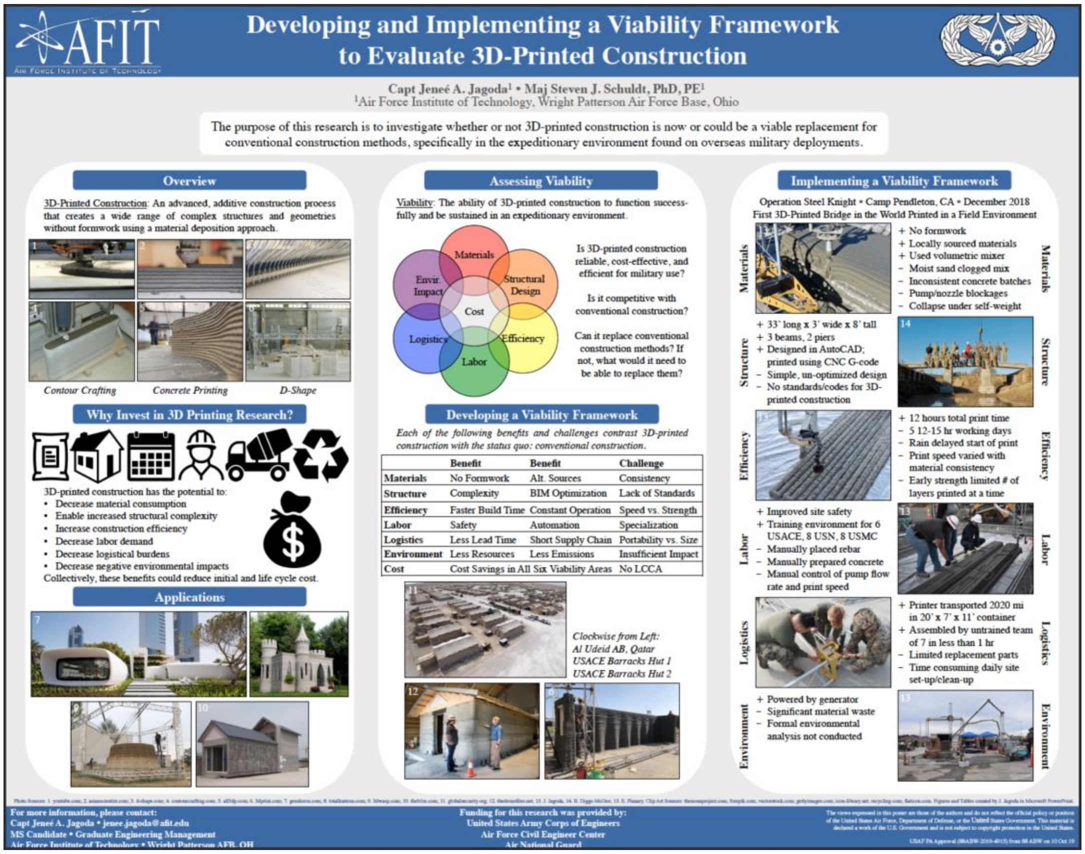
"3D-Printed Construction & Exercise Steel Knight." Oral, Society of American Military Engineers Meeting, Wright Patterson Air Force Base, Ohio. 14 March 2019.

"The Benefits and Challenges of On-Site 3D-Printed Construction: A Case Study." Oral, International Conference on Engineering Technology and Innovation, Belgrade, Serbia. 18 April 2019.

"Developing and Implementing a Viability Framework to Evaluate 3D-Printed Construction." Poster, Dayton Engineering Sciences Symposium, Dayton, Ohio. 29 October 2019.

"Evaluating the Use of 3D-Printed Construction in the Expeditionary Environment." Poster, Air Force Civil Engineer Center Design and Construction Symposium, San Antonio, Texas. 4-5 December 2019.

"A Review of Reviews: Assessing the Viability of 3D-Printed Construction." Oral, International Conference on 3D Printing and Transportation, Washington, D.C. 20 November 2019.


AFIT
Air Force Institute of Technology
Developing and Implementing a Viability Framework to Evaluate 3D-Printed Construction
Capt Jeneé A. Jagoda[1] • Maj Steven J. Schuldt, PhD, PE[1]
[1]Air Force Institute of Technology, Wright Patterson Air Force Base, Ohio
The purpose of this research is to investigate whether or not 3D-printed construction is now or could be a viable replacement for conventional construction methods, specifically in the expeditionary environment found on overseas military deployments.
Overview
3D-Printed Construction: An advanced, additive construction process that creates a wide range of complex structures and geometries without formwork using a material deposition approach.
Contour Crafting
Concrete Printing
D-Shape
Why Invest in 3D Printing Research?
3D-printed construction has the potential to:
• Decrease material consumption
• Enable increased structural complexity
• Increase construction efficiency
• Decrease labor demand
• Decrease logistical burdens
• Decrease negative environmental impacts
Collectively, these benefits could reduce initial and life cycle cost.
Applications
Assessing Viability
Viability: The ability of 3D-printed construction to function successfully and be sustained in an expeditionary environment.
Materials
Structural Design
Efficiency
Labor
Logistics
Envir. Impact
Cost
Is 3D-printed construction reliable, cost-effective, and efficient for military use?
Is it competitive with conventional construction?
Can it replace conventional construction methods? If not, what would it need to be able to replace them?
Developing a Viability Framework
Each of the following benefits and challenges contrast 3D-printed construction with the status quo: conventional construction.
Benefit | Benefit | Challenge
Materials | No Formwork | Alt. Sources | Consistency
Structure | Complexity | BIM Optimization | Lack of Standards
Efficiency | Faster Build Time | Constant Operation | Speed vs. Strength
Labor | Safety | Automation | Specialization
Logistics | Less Lead Time | Short Supply Chain | Portability vs. Size
Environment | Less Resources | Less Emissions | Insufficient Impact
Cost | Cost Savings in All Six Viability Areas | No LCCA
Clockwise from Left:
Al Udeid AB, Qatar
USACE Barracks Hut 1
USACE Barracks Hut 2
Implementing a Viability Framework
Operation Steel Knight • Camp Pendleton, CA • December 2018
First 3D-Printed Bridge in the World Printed in a Field Environment
Materials
+ No formwork
+ Locally sourced materials
+ Used volumetric mixer
– Moist sand clogged mix
– Inconsistent concrete batches
– Pump/nozzle blockages
– Collapse under self-weight
Structure
+ 33' long x 3' wide x 8' tall
+ 3 beams, 2 piers
+ Designed in AutoCAD; printed using CNC G-code
– Simple, un-optimized design
– No standards/codes for 3D-printed construction
Efficiency
+ 12 hours total print time
– 5 12-15 hr working days
– Rain delayed start of print
– Print speed varied with material consistency
– Early strength limited # of layers printed at a time
Labor
+ Improved site safety
+ Training environment for 6 USACE, 8 USN, 8 USMC
– Manually placed rebar
– Manually prepared concrete
– Manual control of pump flow rate and print speed
Logistics
+ Printer transported 2020 mi in 20' x 7' x 11' container
+ Assembled by untrained team of 7 in less than 1 hr
– Limited replacement parts
– Time consuming daily site set-up/clean-up
Environment
+ Powered by generator
– Significant material waste
– Formal environmental analysis not conducted
For more information, please contact:
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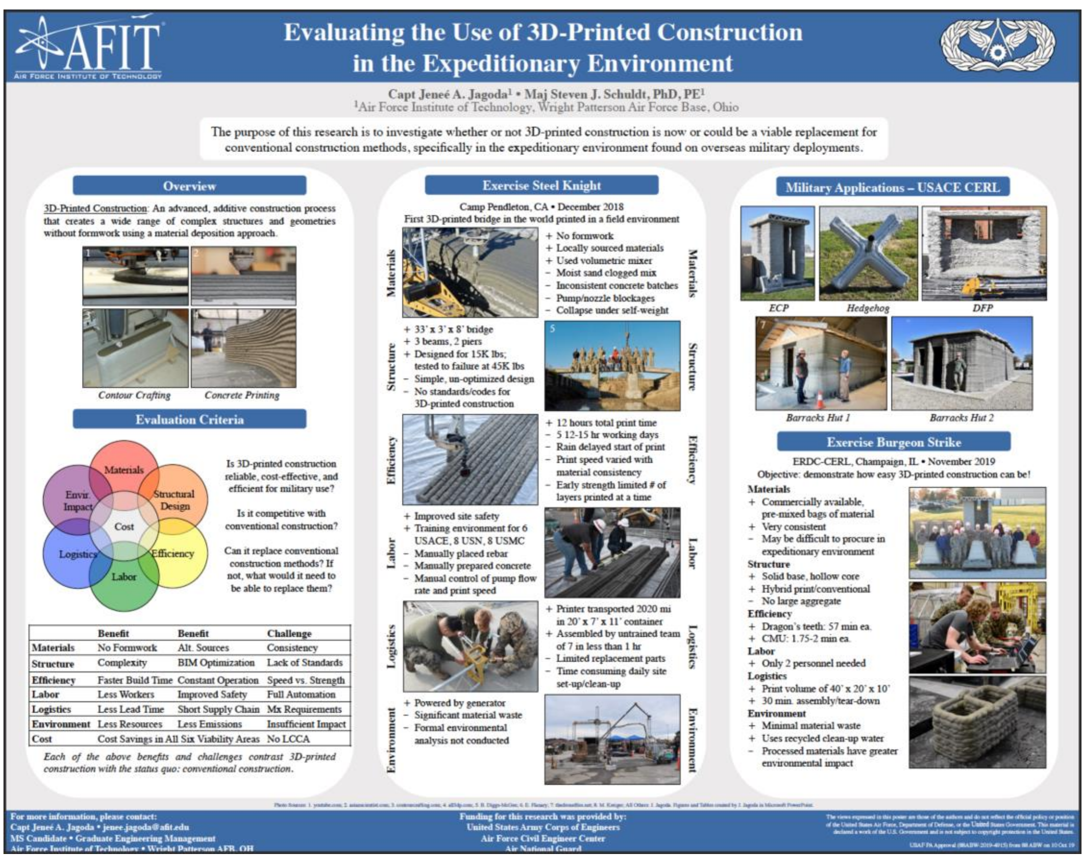
Funding for this research was provided by:
United States Army Corps of Engineers
Air Force Civil Engineer Center
Air National Guard


AFIT
Air Force Institute of Technology
Evaluating the Use of 3D-Printed Construction in the Expeditionary Environment
Capt Jeneé A. Jagoda[1] • Maj Steven J. Schuldt, PhD, PE[1]
[1]Air Force Institute of Technology, Wright Patterson Air Force Base, Ohio
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Contour Crafting
Concrete Printing
Evaluation Criteria
Materials
Structural Design
Efficiency
Labor
Logistics
Envir. Impact
Cost
Is 3D-printed construction reliable, cost-effective, and efficient for military use?
Is it competitive with conventional construction?
Can it replace conventional construction methods? If not, what would it need to be able to replace them?
Benefit | Benefit | Challenge
Materials | No Formwork | Alt. Sources | Consistency
Structure | Complexity | BIM Optimization | Lack of Standards
Efficiency | Faster Build Time | Constant Operation | Speed vs. Strength
Labor | Less Workers | Improved Safety | Full Automation
Logistics | Less Lead Time | Short Supply Chain | Mx Requirements
Environment | Less Resources | Less Emissions | Insufficient Impact
Cost | Cost Savings in All Six Viability Areas | No LCCA
Each of the above benefits and challenges contrast 3D-printed construction with the status quo: conventional construction.
Exercise Steel Knight
Camp Pendleton, CA • December 2018
First 3D-printed bridge in the world printed in a field environment
Materials
+ No formwork
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– Moist sand clogged mix
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– Collapse under self-weight
Structure
+ 33' x 3' x 8' bridge
+ 3 beams, 2 piers
+ Designed for 15K lbs; tested to failure at 45K lbs
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– Limited replacement parts
– Time consuming daily site set-up/clean-up
Environment
+ Powered by generator
– Significant material waste
– Formal environmental analysis not conducted
Military Applications – USACE CERL
ECP
Hedgehog
DFP
Barracks Hut 1
Barracks Hut 2
Exercise Burgeon Strike
ERDC-CERL, Champaign, IL • November 2019
Objective: demonstrate how easy 3D-printed construction can be!
Materials
+ Commercially available, pre-mixed bags of material
+ Very consistent
– May be difficult to procure in expeditionary environment
Structure
+ Solid base, hollow core
+ Hybrid print/conventional
– No large aggregate
Efficiency
+ Dragon's teeth: 57 min ea.
+ CMU: 1.75-2 min ea.
Labor
+ Only 2 personnel needed
Logistics
+ Print volume of 40' x 20' x 10'
+ 30 min. assembly/tear-down
Environment
+ Minimal material waste
+ Uses recycled clean-up water
– Processed materials have greater environmental impact
For more information, please contact:
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Funding for this research was provided by:
United States Army Corps of Engineers
Air Force Civil Engineer Center
Air National Guard

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
26-03-2020	Master's Thesis	September 2018 – March 2020

4. TITLE AND SUBTITLE
An Analysis of the Viability of 3D-Printed Construction as an Alternative to Conventional Construction Methods in the Expeditionary Environment

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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

8. PERFORMING ORGANIZATION REPORT NUMBER
AFIT-ENV-MS-20-M-217

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Civil Engineer Center
Air National Guard
United States Army Corps of Engineers

10. SPONSOR/MONITOR'S ACRONYM(S)
AFCEC, ANG, USACE

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

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

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This research conducts a systematic review of the viability of 3D-printed construction to investigate whether it is now or could be a viable replacement for conventional construction methods, specifically in remote environments where conventional construction capability may be limited. This research then evaluates seven key viability factors – materials, structural design, process efficiency, logistics, labor, environmental impact, and cost – as they apply to two recent, military-run 3D-printed construction case studies. Finally, this research suggests areas in which further research and development is needed in order to ensure the effectiveness of 3D-printed construction in the expeditionary environment.

15. SUBJECT TERMS
3D-printed construction, concrete, expeditionary environment, viability

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** / **19b. TELEPHONE NUMBER** *(Include area code)*
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