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Critical Evaluation of Construction Industry-Related Additive Manufacturing Research: A Scientometric Analysis

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CRITICAL EVALUATION OF CONSTRUCTION INDUSTRY-RELATED ADDITIVE MANUFACTURING RESEARCH: A SCIENTOMETRIC ANALYSIS

THESIS

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Abstract

For decades, the construction industry has been plagued with declining productivity and stagnated growth, thereby driving the need for a disruptive technology such as additive manufacturing (AM) to provide increased architectural freedom and construction speed, reduced labor costs, fewer work-related injuries, and less material waste. Therefore, a valuable perspective can be gained through the review of relevant AM literature to identify the advantages, challenges, and current trends of the research. Through the use of a scientometric analysis of 522 bibliographic records, this research systematically analyzed the state-of-the-art of the construction-related AM research to determine its current status, the key research areas and trends, and the advantages and disadvantages influencing its acceptance. The results of this research found that starting in 2015, AM research in the construction industry has been growing at an exponential rate. This increase was theorized to be the result of AM's growing list of advantages, from reductions in cost and environmental impacts to increased safety and structural optimization. It was also determined that the majority of recent AM research focused on materials and reinforcement topics. These were found to match the most notable challenges of AM, which are material rheology, reinforcement, and lacking construction standards. In addition to the review of literature, this study provides crucial insight into the state of AM research and identifies which areas require more focus and/or innovation before AM becomes an accepted technology in the construction industry and Department of Defense.

To my family, friends, and co-workers who loved, mentored, and supported me through this adventure… You have my sincerest appreciation.

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CRITICAL EVALUATION OF CONSTRUCTION INDUSTRY-RELATED ADDITIVE MANUFACTURING RESEARCH: A SCIENTOMETRIC ANALYSIS

I. Introduction

The large-scale infrastructure construction industry serves as a perfect example of an industry in desperate need of disruptive technology. For decades, the construction industry has been plagued with declining productivity and stagnated growth, thus contributing to its reputation of being slow, costly, wasteful, and dangerous to work in (Camacho et al., 2018; *Wohlers Report 2016*, 2016). However, throughout the last few decades, additive manufacturing (AM), informally known as 3D printing (3DP), has proven its worth in major manufacturing industries and is now poised to change the way infrastructure is built. This is with good reason because AM's implementation in the construction industry could be the disruptive technology needed to correct the problems affecting the industry. With research during the past two decades, AM has been shown to provide increases in construction speed and efficiency while also reducing material waste and labor requirements (Romdhane, 2020). Furthermore, the technology is showing promising potential in the area of infrastructure optimization and reductions to life-cycle costs (Romdhane, 2020). Although the full potential of AM for large-scale infrastructure construction is still unknown, continued research will help that full potential be realized.

Background

The American Society for Testing and Materials (2012) defines AM as "the process of joining materials to make objects from 3D model data, usually layer upon

layer, as opposed to subtractive manufacturing methodologies." The technology was first introduced in 1986 by Charles (Chuck) Hull to automate the manufacturing of geometrically complex components at a more economical rate than traditional machining (Camacho et al., 2018; Yin et al., 2018). Its distinct advantages in allowing mass customization without the need for complex retooling of production equipment greatly decreased associated labor and material waste costs (Yossef & Chen, 2015). These advantages and many others led to AM, or 3DP, being identified as one of the five emerging technologies believed to impact business in the 21st century (Prentice, 2014). Consequently, AM rapidly gained a foothold in the automotive industry before branching out into other industries, including medical and aerospace (Babbar et al., 2021; Bhardwaj et al., 2019).

Beginning in the 1990s, research into the use of AM in the construction industry gained momentum, growing exponentially as interest in the technology and its proposed advantages grew (Nematollahi et al., 2017; Romdhane, 2020). This rapid growth is explained in part by the current state of affairs within the construction industry. Over the last five decades, the construction industry in the United States has experienced a stagnation of growth and declining labor productivity (Nasir et al., 2014). These issues are complicated by the industry's continued reliance on highly-skilled, labor-intensive construction techniques, which also contributes to the industry being repeatedly ranked amongst the highest in worker fatalities (*Census of Fatal Occupational Injuries Summary, 2019*, 2019). Reluctance to adopt innovative technologies or procedures, which plagues the construction industry, has further compounded the problem (Sotorrío Ortega et al., 2020). As a result, a 2016 report from Wohler Associates (*Wohlers Report*

2016, 2016) showed that the construction industry's use of AM techniques only accounted for 3.1% of the total worldwide applications. That being said, more recently the industry appears to be making a fundamental shift to modernization and the embracement of innovated technologies. This new attitude has been a result of the fourth industrial revolution known as Industry 4.0, which has brought with it a wave of research into AM (Sotorrío Ortega et al., 2020).

AM has enormous potential to provide more architectural freedom, increase construction speed, reduce labor costs, cause fewer work-related injuries, and produce less material waste (Wrangler et al., 2016). These numerous benefits have driven the exponential increase in research into the use of AM for facility and infrastructure construction. Research has primarily revolved around solving the many challenges preventing the successful wide-scale adoption of AM in the construction industry. These challenges include material rheology, structural integrity and reinforcement, and construction standards (Panda et al., 2018). Of these challenges, the large majority of published works are of topics relating to material rheology and structural reinforcement, as these areas arguably hold the key to the widespread adoption of additive manufacturing in the construction industry. Breakthroughs in these areas have led to many successful implementations of the technology in laboratory and real-world applications, but with most being implemented in relatively small and highly controlled proof-of-concept experiments (Khan et al., 2020). For this reason, more research into the overarching challenges related to the scalability of AM and its implementation into large-scale construction applications is needed.

Problem Statement

Comparable to the private sector, construction techniques in the Air Force and the Department of Defense (DoD) enterprise have faced technological stagnation, with equal reliance on the same highly skilled and labor-intensive processes. Furthermore, in 2018 the National Defense Strategy brought about a radical shift in thinking for the nation's military forces. With it, combating terrorism, which had been the mainstay of U.S. defense strategies for nearly two decades, was replaced by the new priority of developing a more lethal force capable of competing with near-peer competitors, specifically China and Russia (*National Defense Strategy*, 2018). One of the key components outlined for the development of this more lethal force is the modernization of key capabilities, and with it, a "transition from large, centralized, unhardened infrastructure to smaller, dispersed, and more adaptive basing" (*National Defense Strategy*, 2018). Unfortunately, this demand for an adaptive and agile deployment of hardened infrastructure is a challenging task for the conventional construction practices of today.

Research Objectives

As a result, many organizations, including the Air Force, have a vested interest in continuing the evolution of construction practices and sourcing of new technologies to improve the quality of infrastructure at home and abroad. Technologies such as AM have the potential to revolutionize how the Air Force and DoD perform facility construction, replacement, and base beddown. However, even with its many potential benefits, AM of large-scale infrastructure is still a relatively new concept, and its widespread adoption in the private sector and DoD is still very much unknown. Therefore, this research

addresses the following investigative questions to guide the analysis of the literature and data.

1. *What is the current status of published research regarding AM in the construction industry?*
2. *What key areas of AM's use for construction has the research focused on? Which of these areas share the bulk of the focus? What trends are presented in research topics during recent years?*
3. *What advantages and disadvantages of the technology could influence the adoption of AM practices in construction applications? Are these translatable to meet the requirements of large-scale construction and/or DoD applications?*

Methodology

Due to the rapidly evolving field of AM and the extensive research that has focused on areas such as material rheology and structural reinforcement techniques, a scientometric approach is used to analyze the vast quantities of relevant journal articles and conference papers. This approach provides categorizations of the obtained works and details on the state of the research through clustering, mapping, and visualization techniques. Further visualization techniques, such as keyword frequency and co-occurrence network analysis, will provide even more insight into the obtained research works. The results of this scientometric approach will be interpreted through quantitative and qualitative methods. Quantitative methods such as trend analysis and publication frequency data will be directly used to answer some of the investigative questions, while

qualitative methods will be used to interpret the network visualizations, such as cluster mapping, and answer the remaining investigative questions.

The publications and journals used in the scientometric approach were sourced from Elsevier's SCOPUS electronic database, and they include all results with no restrictions on the published date. The proposed scientometric analysis and visualizations were conducted through the use of four different tools: QSR International's NVivo 12.0, Gephi 9.2, Zotero, and VOSviewer 1.6.17.

Research Limitations

This research is not without limitations, the largest of which is the possibility that the SCOPUS sourced data is not exhaustive; therefore, the exclusion of some published articles related to the topic is expected. However, being that SCOPUS is one of the largest electronic databases, the number of excluded works is likely to be relatively small and is not expected to significantly change the conclusions of this research.

Thesis Organization

This thesis follows the traditional format in which subsequent chapters build on the information provided in previous chapters, thereby culminating in a conclusive response to the central investigative questions. Chapter II consists of a comprehensive review of the current academic literature. The focus of this review will be on the topics and concepts outlined in the investigative questions, while also exploring other unexpected topics that are presented during the scientometric analysis of the data. Chapter III will provide a detailed description of the scientometric methodology,

including search terms, exclusion criteria, and analysis techniques. Chapter IV consists of a discussion of the analysis and subsequent results. Furthermore, the information highlighted in previous chapters will be used to answer the investigative questions, while also exploring the current gaps present in the research and the limitations of additive manufacturing. Finally, Chapter V will summarize the conclusions made during this research before presenting a discussion of the implications and suggestions for future research topics on the subject.

II. Literature Review

The purpose of this chapter is to provide the theoretical and technical groundwork on which the research is based. The first part will introduce the concept of additive manufacturing (AM) and the many technologies that fall within its scope. The following section will then narrow the focus by discussing the various applications in which AM has been applied to the construction industry. Subsequent sections will provide in-depth reviews on the major advantages of AM and current challenges blocking its adoption, respectively. These in-depth reviews will include examples, insights, and opinions sourced from multiple case studies, journal articles, and conference papers from across the literature spectrum. By the conclusion of this chapter, knowledge of the field of AM will have been gained, which is crucial for providing a better understanding of the concepts discussed in future chapters of this research.

Review of Additive Manufacturing Practices

In the modern era, with the ever-growing need to produce products for the consumer at cheaper prices while also limiting adverse external impacts, technology is increasingly leveraged to provide such solutions. The prediction that new and improved technologies will eventually replace conventional manufacturing techniques has been dubbed the fourth industrial revolution, or "Industry 4.0" (Otto et al., 2020). Proponents of this new industrial revolution believe that these emerging technologies will be capable of producing components or parts as efficiently and economically as traditional mass production (Srivastava & Rathee, 2021). One of the technologies at the forefront of this

new revolution is AM, which discards conventional manufacturing practices to produce more complex and efficient components in lesser time. For example, General Electric utilized AM to produce fuel nozzles for its newest turbine engine, transforming what was an assembly of 20 pieces into a single part with a 25% reduction in weight (Buchanan & Gardner, 2019).

Like the components it is capable of producing, AM is not easily defined as one type of practice; rather, it is a combination of many technologies sharing the same basic concept of layer-by-layer manufacturing. That said, ISO/ASTM has published globally accepted guidelines to define the range of AM practices to include seven categories: vat photopolymerization, powder bed fusion (PBF), material extrusion, material jetting, binder jetting, sheet lamination, and directed energy deposition (DED) (Aldoy, 2020; *ISO/ASTM 52900:2021*, 2021; Pessoa et al., 2021). In the remainder of this section, each of these categories will be introduced and briefly discussed. This is intended to provide some context regarding the current state of AM technology and its extensive use throughout the manufacturing world.

Vat photopolymerization is defined by ISO/ASTM as "an AM process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization" (*ISO/ASTM 52900:2021*, 2021). A curable resin, designated as a photopolymer, is hit by a laser-emitted light source to locally solidify it in a step that is then repeated layer by layer until the intended 3D component is produced (Perrot & Amziane, 2019; Pessoa et al., 2021). Vat photopolymerization allows for the production of large but precise, defect-free components at faster speeds compared to other AM practices. However, this

accuracy and speed comes with an expensive price point for materials and post-processing costs (Srivastava & Rathee, 2021).

PBF involves the selective melting (or sintering) of a powdered material, which is spread out in a thin layer on the printer bed, through the use of a high energy or thermal printer head (Pessoa et al., 2021). PBF consists of two sub-categories, depending on the power source involved, known as laser-based PBF (L-PBF) and electron-based PBF (E-PBF) (Srivastava & Rathee, 2021). The advantages of a PBF type system are the high productivity levels, low cost, and wide range of applicable print materials, which includes polymers, thermoplastics, and metals.

Extrusion-based AM is arguably the most common method thought of when discussing AM technologies. Technically speaking, the process is "an extrusion-based AM practice…in which material is selectively dispensed through a nozzle" as defined by ISO/ASTM (*ISO/ASTM 52900:2021*, 2021). The simplified explanation is that extrusion-based AM involves the computer-controlled disposition of material, typically a polymer, ceramic, or metal, to build the 3D component up layer by layer until completion. Fused deposition modeling (FDM) is one of the more common extrusion-based methods, which is used to create concept models, fit and form components, and investment castings at an economically advantageous rate (Srivastava & Rathee, 2021).

Material jetting AM techniques are similar to extrusion-based, as they both involve the controlled deposition of material, but material jetting utilizes material-based droplets and multiple print heads to complete the component. As a result, material jetting allows for better surface properties, safety, superior mechanical and thermal properties, and the exclusion of post-print curing operations (Srivastava & Rathee, 2021).

Consequently, the process is limited by slower build rates, reduced volume, and expensive materials.

Binder jetting techniques are essentially a combination of material jetting and PBF practices, where the powdered material bed is utilized in conjunction with a binder depositing print head (Pessoa et al., 2021). Per ISO/ASTM, "binder jetting processes are those in which a liquid bonding agent is selectively deposited to join powder materials" (*ISO/ASTM 52900:2021*, 2021). Originally developed in 1993, binder jetting allows for the manufacturing of large, complex components from relatively cheap materials, while also maintaining respectable print speeds and eliminating dimensional deformations that could otherwise be caused by other thermally-based AM practices (Srivastava & Rathee, 2021). That said, inconsistent binder penetration into the powder material negatively affects the mechanical performance of the printed components. This, in conjunction with complex post-processing operations, is a cause of great concern (Srivastava & Rathee, 2021).

Sheet lamination involves precisely what the name implies; thin metal sheets of material are combined layer by layer to produce the desired component. The metal sheets are either pre-machined/cut before joining or the entire component is machined post lamination (Perrot & Amziane, 2019). The two common forms of sheet lamination are ultrasonic consolidation (UC) and laminated manufacturing (LOM). Some of the benefits provided by sheet lamination are low component distortion, faster manufacturing speeds, low cost, and the exclusion of any chemical reactions (Srivastava & Rathee, 2021). However, the process is not without drawbacks, as produced components have poor

tensile strengths and shear resistance, poor dimensional accuracy in comparison to other methods, and increased wastage (Srivastava & Rathee, 2021).

The last of the seven AM practices defined by ASTM is DED, which involves similar practices to traditional welding techniques. Per ISO/ASTM, "[DED] is an AM process in which focused thermal energy is used to fuse materials by melting as they are being deposited" (*ISO/ASTM 52900:2021*, 2021). The materials applicable to the DED process, which are polymers, ceramics, and metals, are as numerous as the sub-processes that fall within the DED umbrella. These processes include laser metal deposition (LMD), laser freeform fabrication (LFF), deposited metal deposition (DMD), wire arc additive manufacturing (WAAM), and electron beam freeform fabrication (EBFF), to name a few (Pessoa et al., 2021; Srivastava & Rathee, 2021). The ability to print on existing components allows DED to be utilized for the repair and cladding of damaged parts. That, in addition to DED's higher print speeds, remanufacturing ability, and large build volumes, make it a desirable technology for many fields of manufacturing (Srivastava & Rathee, 2021). Unfortunately, the use of thermal energy can lead to component distortion, resulting in poor accuracy and surface finish, which is one of the major negatives of DED (Srivastava & Rathee, 2021).

While the field of AM technology is vast and continually growing, as shown by the seven categories discussed in this section, research specific to AM applications in the construction industry has not expanded into all seven categories. The next part of this chapter will provide a deeper and more detailed look into which techniques are being researched for construction industry applications and the implications involved. This more in-depth review will provide greater context on the extent of AM research for the

construction industry, the hypothesized advantages, and current issues hindering the technology's advancement into practical use.

Additive Manufacturing in Construction

When the concept of AM was first introduced during the 1980s, the construction industry largely overlooked the concept, even as great strides were being made in the automotive, medical, and aerospace industries. It was not until the 1990s that the technology started gaining attention and research towards its application in the construction industry began to grow (Romdhane, 2020). That said, the concept of AM, which is defined by ASTM as "the process of joining materials…layer by layer," means that the construction industry has arguably been utilizing AM-type processes since as early as the beginning of the 20th century (*ISO/ASTM 52900:2021*, 2021). For example, slip-form construction consists of a process where mechanized formwork moves automatically in a vertical or horizontal direction while the construction material is continuously deposited, layer-by-layer until complete (Khan et al., 2020; Vélez et al., 2020). Khan et al. (2020) state that slip-forming has been widely used to construct offshore facilities, interstates, and runways for decades. Using the runway expansion at Fort Lauderdale-Hollywood International Airport in Florida as an example, which utilized automated guidance and slip-form techniques, Khan et al. (2020) argue that this could be considered 3D printing (3DP). Support of Khan et al.'s (2020) claim can be found in Asprone et al. (2018), who explain the AM technique of slip forming using a robot-guided form and computer-controlled material distribution. However, the preponderance of researchers agree that the majority of AM technology actively being

researched today for application in the construction industry falls within three categories, as shown in Figure 1: Contour Crafting, Binder Jetting, and Concrete Printing. While other methods will be introduced later in this section, the primary focus will fall on these three categories in keeping with the literature.

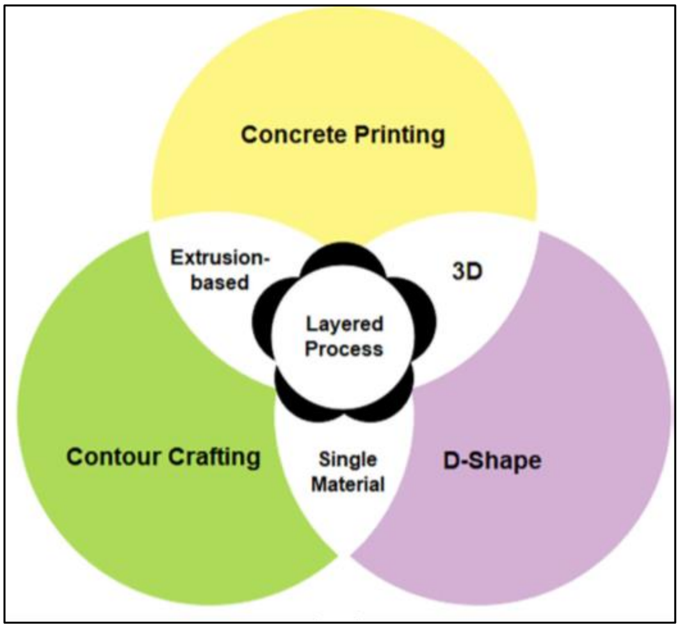


Figure 1. Comparison of Top 3 AM Categories for Construction (Lim et al., 2012)

Furthermore, being that concrete, with its relatively low cost and suitable material properties, is the most commonly used and widely available construction material around the world, it is the ideal media for printing in construction (Khan et al., 2021). As a result, the majority of construction industry-related AM research is focused on the application of ceramic printing techniques; therefore, terms such as 3D Concrete Printing (3DCP) and 3D Printed Concrete (3DPC) are used interchangeably with AM (Lao et al.,

2021). Any relevant research into the use of alternative materials for AM construction will also be included later in this section.

Contour Crafting

Contour Crafting (CC) is an extrusion-based AM technology that was developed by Dr. Khoshenvis at the University of Southern California in 1998 (Otto et al., 2020). Khoshnevis (2004) defines CC as an "additive fabrication [manufacturing] technology that uses computer control to exploit the superior surface-forming capability of troweling to create smooth and accurate planar and free-form surfaces." CC is unique because it was the first AM technology proposed for use in the construction industry (Al Rashid et al., 2020).

In keeping with the AM definition, CC utilizes 3DCP techniques to extrude the construction media layer-by-layer, thus allowing sufficient time for lower layers to develop enough green strength to support the upper ones (Hamidi & Aslani, 2019). The key feature of CC is the use of integrated trowels to refine the surface finish of the extruded media, with a top trowel to smooth the top of the media and a side trowel to refine the external surface finish (Khoshnevis, 2004). The advantages of CC are that the design of its nozzles allows it to deposit more material when compared to the other two techniques, which results in lesser build times (Al Rashid et al., 2020). Consequently, Babbar et al. (2021) state that using CC makes it possible to create a room in an hour and a 200 square meter single-story house in a day. Krause et al. (2018) discuss similar advantages regarding the Technical University of Dresdren's Concrete ON-site 3D-Printing (CONPrint3D) program, which is expected to bring 25% cost savings with 400-600% faster execution times.

Furthermore, Khoshnevis (2004) states that the superior characteristics of CC allow for the mechanized installation of plumbing and electrical services and that adobe-type structures can be rapidly produced without the need for additional support beams. Therefore, the installation of doors and windows would be the only step requiring human input, thus making CC a seemingly automated process (Allouzi et al., 2020; Khoshnevis, 2004). CC also offers the opportunity for reinforcement, albeit with conventional methods, by placing rebar in the hollow sections of the printed walls/columns and pouring self-leveling concrete (De Schutter et al., 2018; Mechtcherine & Nerella, 2018b). Unfortunately, X. Zhang et al. (2019) believe that the main reasons hampering the industry adoption of CC are the lack of successful cases to corroborate its feasibility and the scarcity of valid models to monitor and control costs.

Binder Jetting

The term "Binder Jetting" refers to all particle bed-based AM techniques, such as selective binder activation and selective paste intrusion (Al Rashid et al., 2020). This clarification is necessary because many of the literature documents utilize multiple different terms to describe the same technique, which is to be expected in a developing research field where information is likely out of date before its publication (Bos et al., 2016). That said, the binder jetting process begins with the deposition of powdered material, typically sand or cementitious-based, which is then followed by the printhead containing spray nozzles for the liquid binder (Ma et al., 2018; Mai et al., 2021). This process is repeated layer-by-layer until the component is completed in a similar fashion to CC. Because binder jetting utilizes a powder bed, the material below supports the structure being printed above, which allows for components to be manufactured without

the geometrical design constraints, like overhangs, cantilevers, and voids, found in other 3DCP technologies (Al Rashid et al., 2020; Hamidi & Aslani, 2019). Furthermore, post-processing steps such as heat treatment and infiltration can be used to improve the printed component's strength and durability (Hamidi & Aslani, 2019).

J. Pegna was the first to adopt binder jetting techniques, more specifically selective deposition, and apply them to construction (Lowke et al., 2018). The method introduced consisted of the deposition of a cement-based binder over a layer of sand, followed by its rapid curing through exposure to steam (Lowke et al., 2018). The resulting components exhibited anisotropic behavior and maximum compressive strength of 33.8 MPa when tested perpendicular to the printing plane (Al Rashid et al., 2020).

One of the challenges associated with binder jet technology is the need to balance particle size with binder penetration because a mismatch can lead to an increase of voids within the finished component (Feng et al., 2015; Mai et al., 2021; Yu et al., 2020). The common way of avoiding this condition is to use a small particle size, which contributes to binder jet techniques being much slower when compared to extrusion-based AM like CC (Yu et al., 2020). Xia et al. (2019) noted that increased fly ash content improved binder penetration over time, as the fly ash reduced the average particle size of the powder bed material. Lowke et al. (2020) researched this dilemma by observing the material characteristics of completed components with varying jet pressures. Interestingly, an increase in jet pressure only moderately increased material strength at the cost of increased porosity and reduced shape accuracy (Lowke et al., 2020). Similarly, Mai et al. (2021) explored the issue of poor binder penetration when using large particles through the incorporation of shotcrete fundamentals. This method, dubbed

Large Particle 3D Concrete Printing (LP3DCP), produced components with maximum compressive strengths of 64.1 MPa during initial material testing (Mai et al., 2021). Mai et al. (2021) concluded that these results confirmed that LP3DCP could be a viable technology for the construction industry, and further development would continue to improve the material properties.

The most prolific form of binder jet technology for construction is D-Shape (Paolini et al., 2019). D-Shape technology was developed by Enrico Dini from Monolite UK Ltd. as competition to the more traditional extrusion-based 3DCP techniques (Cesaretti et al., 2014). D-Shape printers differ from these machines as they follow the traditional binder jet method of combining sand or cement-based materials with a binder, typically magnesium-based, to create solid objects (Paolini et al., 2019). Components printed using D-Shape have exhibited compressive strengths in the range of 235-242 MPa (Al Rashid et al., 2020). Ma et al. (2018) state that D-Shape has been proven to be very effective at creating large-scale structures and that the European Space Agency (ESA) is researching the technology for use in constructing a lunar base. Furthermore, Krassenstain (2014) claimed that D-Shape could allow the military to rapidly construct critical infrastructure, such as bunkers and hospitals, much faster than conventional construction techniques. However, opinions on the usefulness of D-Shape for creating large-scale infrastructure are still conflicting, as Hamidi et al. (2019) argue that the size of the component is restricted by the printing space.

<u>Concrete Printing</u>

The Concrete Printing method was the product of extensive testing by the University of Loughborough and is similar to CC, as it also utilizes an extrusion-based

approach to AM (Perrot & Amziane, 2019). The key difference between the two technologies is that Concrete Printing foregoes the use of trowels found in CC. This exclusion allows for greater control of internal and external geometries, which provides Concrete Printing the capability to create highly customizable components, but at the cost of a lower quality of the surface (Hamidi & Aslani, 2019). This rough surface finish can be corrected, but only through post-processing operations to smooth freshly printed layers or grind the finished and cured component (Lim et al., 2012). Unfortunately, these post operations require the use of human labor and/or produce waste, thus countering two of the key advantages of AM found in the literature.

To reduce the human component, Canou et al. (2021) presented a novel method for automating the subtractive method of 3DCP finishing operations, which was already integrated into their Hybrid INDustrial CONstruction (HINDCON) project, but the process still produced an unavoidable amount of waste. An alternative method to correct this rough surface finish was also explored by Lao et al. (2021), who developed a variable-geometry nozzle that was optimized through pre-set geometries and based on the contour required by the 3D model. Initial testing of this variable-geometry nozzle showed improvements in the surface finish of 38% when compared to conventional 3DCP nozzles (Lao et al., 2021). Concrete Printing also retains the ability to produce functional voids within the completed component for reinforcement, utility installations, or other purposes. Consequently, unintentional voids are more common in Concrete Printing, which negatively affects the final performance of the printed material (Hamidi & Aslani, 2019).

Additional Additive Manufacturing Techniques

Other AM technologies found in the literature that have been explored for construction applications are freeform construction, shotcrete, injection 3DCP (I3DCP), WAAM, rock printing, and an assortment of mobile printing techniques. Freeform construction was developed in response to the lack of flexibility to make freeform structures when using traditional extrusion-based techniques. An example of freeform construction involves the printing of thermoplastic shells to be used as casting molds for traditional concrete, thereby resulting in double-curve structures (Al Rashid et al., 2020). However, the potential of the concept has yet to be applied at the commercial scale. Another example of freeform construction described in the literature is what researchers at ETH Zurich dubbed "Smart Dynamic Casting" (Al Rashid et al., 2020; Asprone et al., 2018). This technique is essentially slip-forming with digital control, where fresh concrete is poured into a mold that automatically rises as the bottom layers obtain a sufficient green strength to support progressive layers (Mechtcherine & Nerella, 2018a).

The shotcrete 3D printing process (SC3DP) functions in the same way that conventional shotcrete practices do but with the assistance of computer-controlled deposition (Kloft et al., 2019, 2020). The advantage of SC3DP over other 3DCP methods is that the kinetic energy of the delivery system improves the compaction and mechanical bond characteristics of the concrete. This method also allows for the integration of more conventional reinforcement techniques, which is a challenge for many 3DCP processes. Limitations of SC3DP are the same as conventional shotcrete, being that the deposition method restricts the size of aggregate, which increases material cost and affects the final performance characteristics of the concrete (Kloft et al., 2019, 2020).

SC3DP also involves the use of traditionally placed reinforcement, which is what García de Soto et al. (2018) improved on with their Mesh Mould Wall (MMW) concept. In MMW, a semi-autonomous robot fabricates (cutting, bending, and welding) and tensions a steel mesh into the shape of the required component (García de Soto et al., 2018). This mesh serves two purposes, the first being the reinforcement of the piece and the second being the mold for the concrete, which is tailored for MMW. Initial trials showed great potential, especially when constructing geometrically complex pieces, and García de Soto et al. (2018) hinted that future research would mature the method.

Lowke et al. (2021) discuss the idea of I3DCP and how it has been used in various trials to test its applicability for construction applications. I3DCP differs from other 3DCP methods as the concrete extrudate is printed into a carrier liquid (typically a gel) that suspends the structure until cured. This concept allows for the construction of complex truss structures without the need for exterior supports or consideration of gravitational forces. I3DCP has been demonstrated numerous times by the French company Soliquid on a large scale when it produced a 2.5-ton artificial reef structure called BathyReef (Lowke et al., 2021).

WAAM, which is a subset of the DED print method, has been gaining interest as a means of printing metal structural components and/or reinforcement. These metal components can be produced in highly optimized shapes that would otherwise be too expensive or impossible to create using conventional techniques, and they can be combined with conventional structural members to create hybrid structures (Buchanan & Gardner, 2019). The MX3D bridge in Amsterdam, which was completely fabricated

using WAAM, is a very recognizable example of the successful employment of AM to complete fully printed metal structures.

The rock printer technique was developed by ETH Zurich, in collaboration with the Massachusetts Institute of Technology (MIT), and is a novel concept that produces structural components using rock and textile filament (Al Rashid et al., 2020). This process uses a 3D robotic arm which binds the rock with the filament in a programmed manner to create the required structure. The bound structure also has the added benefit of being fully dissembled if needed. This technique was demonstrated by building a 13-ft tall column, which was disassembled at a later date and produced zero waste.

Most AM machines are commonly based on a cartesian coordinate (XYZ-axis) system with either a gantry-type assembly using a three-motion nozzle assembly or a six-axis robotic arm (Ghaffar et al., 2018; Pacillo et al., 2021). These stationary systems complicate the application of AM for large structures as the printer (or print area) would need to be bigger than the structure being printed (Vélez et al., 2020). As a result, many researchers have proposed a variety of mobile AM systems. For example, Vélez et al. (2020) provided a possible mobile solution through the use of a continuously climbing printer, or Koala 3D, but the concept has not been applied on large scale yet. Rivera et al. (2020) also explored the use of mobile 3D printers to circumvent the restrictions of a stationary printer, which was successful in proving the concept in simulated, computer-based trials. Additionally, Zhang et al. (2018) tested the effectiveness of utilizing multiple robots (printers) to complete a single work piece and determined that multi-robot integration is possible. This theory of multiple robots is shared by research teams at MIT

who introduced the Swarm concept or essentially the idea of using many robots to complete one larger task (Al Jassmi et al., 2018).

Advantages of Additive Manufacturing

AM has been classified as a disruptive technology, meaning that its adoption is not simply done through integration into the current practices of the adoptee, in this case, the construction industry (Besklubova et al., 2021; Kothman & Faber, 2016). Rather, to adopt a disruptive technology like AM, the industry must rethink the entire process of how components and infrastructure are built. As expected, this is not an easy process to achieve, let alone begin, so the disruptive technology must provide a distinct advantage over what the current system provides (Alchaar & Al-Tamimi, 2021; Besklubova et al., 2021; Saade et al., 2020). In the context of AM for construction, the most commonly cited advantages are its potential to reduce costs through increased efficiencies and material usage, improve job site safety and associated costs by reducing labor requirements, reduce environmental impacts of the construction industry, and integrate smart infrastructure techniques into new construction (Besklubova et al., 2021; Bester et al., 2021; Y. Chen et al., 2022; Pacillo et al., 2021).

Cost Reductions

The saying, "Money makes the world go around…" was first popularized after being sung in the Broadway classic "*Cabaret*" to imply that money is the most important thing in life. Similarly, the potential economic benefits of AM are the most important advantages referenced in the literature (Kreiger et al., 2020). These economic benefits stem from two key focus areas leveraged through AM technology, which are the

reduction in material usage and the integration of digital design, to bring unrealized efficiencies into the industry.

The construction industry generates an enormous amount of waste, which is estimated at 80% of the worldwide total in 2011 (Sanjayan & Nematollahi, 2019; Shahzad et al., 2020). Fortunately, the most recognizable feature of nearly all AM technologies is the lack of formwork needed to produce the intended component, formwork that would otherwise be required in conventional methods and then disposed of. Formwork accounts for roughly 35-60% of the total cost of conventional concrete construction; these are costs that are not incurred in 3DCP (Camacho et al., 2018; Shakor et al., 2019). The elimination of formwork also reduces labor costs and time requirements associated with the installation and eventual disposal of formwork post-cast.

Alternatively, in a recent study by Han et al. (2020), AM was used to produce rather than eliminate formwork. Han et al. (2020) argue that benefit of this method is that the 3DP carbon fiber reinforced (20%) ABS polymer formwork can be reused over 10 times more than conventional wood or foam formworks. Similarly, Poullain et al. (2018) describe utilizing printed formwork and then leaving it as a permanent feature. The Batiprint3D technique, which was co-developed by the University of Nantes' Laboratory for the Sciences of Numerics and the GeM Research Institute in Civil Engineering and Mechanics, works on a three-layer wall system, where two layers of polyurethane foam are printed to form the permanent formwork for the third layer of self-compacting concrete (Poullain et al., 2018). After curing, the foam layers are left in place to act as thermal insulation, thereby eliminating any installation/demolition step(s) that would

otherwise be present in conventional in-situ casting. Keating et al. (2017), from MIT's Mediated Matter Group, also developed a permanent formwork system similar to Batiprint3D but integrated it into a self-contained, solar-powered mobile system called the Digital Construction Platform (DCP), shown in Figure 2. Like Batiprint3D, the DCP also utilized 3DP foam as the permanent formwork and insulation material to produce structures with essentially zero waste (Keating et al., 2017).

Figure 2. MIT Mediated Matter Group's DCP Concept (Keating et al., 2017)

AM also provides the added benefit of reducing the amount of construction material used (Allouzi et al., 2020). This reduction is accomplished through two means, with the first being the elimination of over-ordering material and subtractive construction methods that produce waste (Shakor et al., 2019). By its nature, AM components only consume enough material to complete the piece, which is in stark contrast to conventional

methods (Allouzi et al., 2020). This is especially true in binder jetting construction techniques, where the powder-based material that is left over can easily be recycled to produce the next component (Hamidi & Aslani, 2019). Furthermore, 3DCP's ability to incorporate channels and space for plumbing, electrical, and other utility requirements consequently reduces the time required for post-cast procedures and their associated labor costs (Allouzi et al., 2020; Valente et al., 2019). The benefits of AM are not only limited to concrete; Jia et al. (2021) explored the possibility of using AM to print fiber reinforced gypsum composite (FRGC) to reduce waste and tooling expenses. They concluded that AM produced an effective FRGC and future research could continue to build on the technology.

The second way AM can reduce the consumption of materials is through structural optimization or topology. In conventional construction, such as pre-cast methods, the economy of scale drives design philosophy, which leads to components being as consistent with one another as possible. This philosophy is supported by Weng et al. (2020), who compared the economic and environmental costs of a pre-cast public bathroom unit (PBU) to one produced by 3DCP, where it was found that pre-cast outperformed 3DCP if more than 75 PBUs were required. However, 3DCP was the better option when producing less than 75 PBUs or when compared to traditional in-situ methods (Weng et al., 2020).

Using the study by Weng et al. (2020), this economy of scale methodology can also lead to the over-engineering of components and inefficient use of resources and materials, especially when not producing the components in the scale required to make pre-cast techniques cost-effective. AM could provide the solution to this problem by

giving an economical means to produce structurally optimized components based on their given function (Camacho et al., 2018). This is because AM can make customized components at no additional cost when compared to a standardized design since the custom component requires less material and/or time (De Schutter et al., 2018). This gives AM the potential to efficiently and effectively mass produce customizable structures (Wu et al., 2016).

In terms of non-in-situ components, this structural optimization also allows components to be much lighter, as evidenced in Weng's (2020) PBU comparison where the printed component weighed 26.2% less than the conventionally casted part. This reduction in material and weight also provides environmental benefits, as less cement is required to produce the component and smaller equipment can be used to transport and assemble them (Han et al., 2021; Muñoz et al., 2021). That said, more details on the environmental benefits of AM will be reviewed later in this section.

Allouzi et al. (2020) also explored the cost benefits of AM in their cost comparison study for a multipurpose hall in Jordon. In the theoretical study, they found that the 3DPC hall used significantly less material, resulting in a 65% reduction in construction cost (Allouzi et al., 2020). Similarly, Tobi et al. (2018) concluded that a 3DP house could provide up to a 30% reduction in cost when compared to a traditional home in the United Kingdom. In 2018, a cost comparison experiment/demonstration, conducted by the U.S. Army's Engineer Research and Development Center -Construction Engineering Research Laboratory (ERDC-CERL), used 3DCP to construct two traditional barracks huts (B-huts) and compared the cost differences (materials and labor) with conventional methods. Their findings showed a 10-25% reduction in cost versus a

similar CMU structure and 25-37% less cost than a conventionally cast-in-place structure (Kreiger et al., 2020).

Material reductions are also the result of the second key area where AM is cited to bring economic advantages, which is its ability to be integrated with digital design. For example, the integration of AM with digital design and on-demand processing reduces the chances of material waste through the over-ordering of construction material like concrete (Shakor et al., 2019). However, digital integration not only reduces material consumption; it also increases the overall productivity of the entire construction process. This is important, as referenced by Nasir et al. (2014), who compared the labor productivity growth rate in 20 countries and found that the U.S. had the worst performance, with an annual compound rate of -0.84%. Additionally, every 1% increase in world productivity could save $100 billion in construction costs per year (Xu et al., 2021). As a result, many researchers are looking for ways to improve the productivity of the construction industry, with one being the ability of AM to integrate into Building Information Modeling (BIM) (Weng et al., 2021).

BIM is a comprehensive digital construction management approach that combines modeling, construction planning, cost estimation, and post-construction facility management practices, while also incorporating material, resources, equipment, and manufacturing data, in a single package (Weng et al., 2021). Not only would this integration have immediate effects on productivity, as referenced by Weng et al. (2021), but it would also provide project managers with the capability of producing on-demand components directly from digital CAD files. The benefits of this integration were theorized by Camacho et al. (2018), who said that an on-site 3D printer could produce

customized components resulting from unforeseen design modifications and/or alleviate production delays. This elimination of production delays can also prevent the temptation to work out of sequence, which commonly introduces laborers to unnecessary risks (Camacho et al., 2018). Davtalab et al. (2018) even proposed an interoperable BIM-integrated system that would be capable of interacting, analyzing, and controlling a robotic construction system. This digital integration with BIM also allows for reusable design data, potentially reducing planning costs to negligible amounts when constructing multiple iterations of the same structure or component (Abakumov et al., 2021; De Schutter et al., 2018; Weng et al., 2021).

Increased Safety

As stated earlier, the construction industry is heavily reliant on the use of manual labor. According to the International Labor Organization (ILO), the industry accounts for 8.4% of employment across the globe, with many of these jobs involving physically demanding and hazardous work (Hossain et al., 2020; Pacillo et al., 2021). Furthermore, labor accounts for at least 25% of total project cost, and the effects of unskilled and/or labor shortages can result in costly project delays or accidents (Hossain et al., 2020). One way to combat the inherently dangerous work environment, lower the risk of human error, and prevent potentially deadly mishaps is to reduce or eliminate human involvement through automation (Pacewicz et al., 2018). Valente et al. (2019) believe that AM has the potential to drastically reduce labor costs as the technology requires very minimal human interaction to operate. The prospect of replacing humans with machines is not foreign to the construction industry; Hossain et al. (2020) state that AM is likely to be the next technology in line to replace manual tasks, similar to how hydraulic

earthmovers replaced the manual shovel. While this depiction may be dramatic, adoption of AM techniques in construction would dramatically reduce the demand for laborers otherwise needed for conventional construction tasks, while also increasing the demand for higher skilled workers to operate and integrate the technology.

Environmental Benefits

Ever since the dawn of the Industrial Age, the construction industry has created significant amounts of wealth through the transformation of raw materials, energy, and labor, unfortunately at the cost of enormous negative impacts on the environment (Han et al., 2021). The construction industry is responsible for 40% of global energy consumption, 38% of global greenhouse gas (GHG) emissions, 12% of global potable water use, and 40% of solid waste generation in developed countries (Lowke et al., 2021; Mai et al., 2021). For this reason, the construction industry is in desperate need of a solution like AM, as it has the potential of reducing the negative environmental effects of conventional construction practices. This reduction can be accomplished in many ways, including reductions in material waste; utilization of sustainable, recycled, or alternative materials; impacts from activities such as material transportation; and life-cycle costs of the constructed infrastructure (Wu et al., 2016).

The first of these environmental benefits, being reductions in material waste, has already been discussed earlier in this review so further investigation is not needed. That said, it is important to recognize the potential second and third-order effects of reducing things like material waste, particularly concrete. This is because the unfortunate truth of concrete, more specifically the manufacturing of cement binder (e.g., Ordinary Portland Cement (OPC)), is that the high amounts of energy required for its production account for

a huge portion of total carbon dioxide emissions globally (5-7%) (Han et al., 2021; Mai et al., 2021; Şahin et al., 2021). Furthermore, the production of OPC and concrete also require significant amounts of raw materials such as fresh water, aggregates, clay, limestone, etc., which causes negative impacts to the environment during extraction (Şahin et al., 2021). As a result, the construction industry is continually looking for ways to reduce the use of traditional cement binder, OPC, and other natural resources in its concrete mixes (Biernacki et al., 2017; Khan et al., 2021).

The most commonly cited method of reducing the environmental impact of concrete is to replace its components with sustainable and/or recycled materials. Note that while the technological strides in the use of sustainable resources for concrete undoubtedly reduce the environmental impact of traditional construction techniques, this review will focus on the literature from the perspective of AM. For example, Hager et al. (2016) suggested that sulfur-based concrete could be used as a replacement for traditional OPC-based mixes (Alkhalidi & Hatuqay, 2020). This incorporation of sustainable ingredients like sulfur or recycled aggregate could potentially reduce the negative impacts of traditional OPC production and its increased use in 3DPC mixtures (Han et al., 2021).

Khan et al. (2021) explained that recycled aggregates provide three advantages: reducing new resource demand, reducing landfill contributions, and reducing energy demands for production. Mai et al. (2021) found that incorporating natural or recycled coarse aggregates into their LP3DPC resulted in a non-renewable primary energy demand reduction of 30% in comparison with conventional mixes. Consequently, this also results in a 30% lower potential for global warming and acidification values (Mai et al., 2021).

Zou et al. (2021) found that replacing natural sand with 100% recycled sand increased the green strength properties of the 3DPC mortar, a critical material attribute, while still maintaining its printability through the inclusion of a sodium gluconate admixture. Zaneldin et al. (2021) found success in their study about utilizing AM technology, specifically FDM, and plastic waste to create feasible alternatives to traditional construction elements, such as lightweight and ultra-lightweight concrete hollow blocks and lightweight concrete bricks. The results of their study found that the 3DP recycled plastic components were 41% less expensive to produce when compared to bricks and had higher compressive strength than blocks and bricks (Zaneldin et al., 2021).

Cuevas et al. (2021) explored using waste glass aggregate and expanded thermoplastic microspheres (ETM) to create a more sustainable 3DP lightweight concrete (3DPLWC) mixture. Their results found that when incorporating a 50/50 waste glass/basalt aggregate and ETM, flexural strength improved, compressive strength increased by 22%, and thermal conductivity decreased by 38% (Cuevas et al., 2021). Muthukrichnan et al. (2020) used rice husk ash (RHA) to substitute 20% of OPC in a cementitious mortar mixture with favorable printability characteristics and high green strength. Similarly, Kaszynska et al. (2020) experimented with various mixtures utilizing differing amounts of silica fume and fly ash as substitutes for a percentage of OPC and limestone powder as a substitute for 20% fine aggregate. The findings from this experiment produced a suitable 3DPC mix that provided an 8-13% reduction in cost and a 17% lower environmental impact (Kaszyńska et al., 2020). Iubin et al. (2018) also examined ways of substituting OPC with clay soil in 3DPC and found that a 5-25% substitution leads to a stiffness increase of 11-34% with only slight reductions in

compressive strength of 0.5-6.8%. Ghaffer et al. (2018) note that AM could also help reuse and recycle demolition waste from previous structures, thereby creating a circular economy in the construction industry. This idea is supported by Labonnote et al. (2016), who asserted that AM could reduce construction waste from subtractive construction methods and single-use formwork.

While research into sustainable concrete ingredients is extensive, there are current AM technologies and materials that do not use an OPC-based material and instead utilize alternative materials to print components (Shahzad et al., 2020). Perrot et al. (2018) added alginate seaweed biopolymer to an earth-based material to improve the development of green strength, thus making it viable for printing. Shahzad et al. (2020) explored the use of solid-waste-based sulfoaluminate high-activity material (SHAM) as a replacement for OPC and developed a suitable 3DP mixture with compressive strengths up to 97 MPa. This SHAM mixture also had the added benefit of being significantly cheaper than OPC; since it used industrial byproducts, the mixture was considered a green approach by the authors (Shahzad et al., 2020).

The World's Advanced Saving Project (WASP), based in Italy, has the primary focus of utilizing AM techniques with natural mixtures, such as soil and straw (Camacho et al., 2018). This soil and straw mixture, known as cob, has been used in conventional construction methods around the world (Gomaa et al., 2021). According to Gomaa et al. (2021), the use of cob has been explored in many AM trials so far, which have found that 3DP cob displays competitive thermal performance when compared to traditional materials (concrete, brick, etc.) and conventional cob construction. Another important

trait of cob is that its environmental performance (i.e., less impact) is significantly better (83%) when compared to 3DPC, as evidenced in a study by Alhumayani et al. (2020).

Another major source of negative environmental effects (and cost) resulting from the construction industry comes from the transportation of raw materials and completed components commonly found in pre-cast/fab operations (Otto et al., 2020). This is evidenced in numerous case studies that find that transportation accounts for significant percentages of environmental impacts (Alhumayani et al., 2020; Han et al., 2021). The advantage of AM technology is that components can be produced in-situ, or at a lighter weight, allowing for the transportation of more components per trip for a more efficient transportation means (Muñoz et al., 2021; Weng et al., 2020). The elimination of transportation costs is the main goal of the case study by Li et al. (2021), who explored the feasibility of utilizing seawater and coral sand for use in a 3DPC mortar. They state that coastal regions and small islands tend to not have readily available fresh water and river sand resources, which increases the cost and environmental impact of concrete due to the need to transport those materials. Initial trials supported the claim that seawater coral sand mortar had great potential to be used in 3DCP technology, albeit with fiber reinforcement (Li et al., 2021). The advantage of eliminating transportation costs with in-situ AM is currently being explored by NASA and ESA, who are interested in adapting AM technology for its possible use on the Moon and/or Mars (Cesaretti et al., 2014; Liu et al., 2021; Mueller et al., 2017). Other concepts regarding the use of indigenous materials to reduce transportation costs (economical and environmental) are shared by Hamidi and Aslini (2019). Furthermore, Labonnote et al. (2016) argue that the same methods of using indigenous materials can be applied for disaster relief and

contingency locations, where suitable construction resources may be non-existent or already consumed.

In addition to reducing the environmental impacts related to the construction of a component, it is crucial to explore the life-cycle of that component and properly grasp the complete environmental impact that will occur. The preferred approach to measure the complete impact of a component is life-cycle analysis (LCA) (Saade et al., 2020). An LCA that was conducted to study the effects of AM processes in the manufacturing industry determined that the cumulative energy demand required for the production of a single component can be reduced by 41%-64%, along with reduced emissions and environmental impacts (Ma & Wang, 2018). Ma and Wang (2018) argue that similar benefits could be attributed to AM in the construction industry.

This is supported by Muñoz et al. (2021), who theorized that AM has benefits in reducing the life-cycle costs of the construction phase and the completed infrastructure. This theory is backed by the results of the LCA, in which Muñoz et al. (2021) concluded that GHG emissions were 38% lower when using AM techniques to construct a single structural pillar. However, they also found that if conventional methods were used on a larger scale, and the mold was reusable, then the total GHG emissions for a large number of pillars would slowly approach that of an equal number of printed pillars (Muñoz et al., 2021). In addition, Mohammad et al. (2020) found that the higher cement content found in most 3DPC formulas contributes to higher negative environmental impacts, and it only surpasses conventional methods by 20% when unreinforced. That said, the LCA used reinforcement based on conventional methods, which may not be the best option for 3DPC. Another LCA conducted by Mahadevan et al. (2020) found that 3DPC failed to

provide sufficient thermal performance when compared to M25 concrete and first-class bricks. Unfortunately, their study did not include any topological optimization of the 3DP structure, which is a key advantage of 3DCP.

Lastly, while not directly related to a component's environmental impact, Bayley and Kopac (2018) published the results of a cost-based LCA which found that AM could reduce the costs and execution timeline for disaster relief or contingency structures. They explained that 3DCP facilities, when compared to traditional steel or timber structures, could be produced at an equal rate while also being more durable and with increased longevity (Bayley & Kopac, 2018). Schuldt et al. (2021) support this opinion by stating that AM provides permanent or temporary facilities that could withstand additional destructive forces when conventionally constructed facilities may be rendered inoperable.

<u>Optimization Potential</u>

The final major advantage of AM referenced by the literature includes previously discussed concepts of design freedom and structural (topology) optimization, which allow engineers to adapt AM to produce smart infrastructure (Khan et al., 2021; Volpe et al., 2021). Smart infrastructure is defined as infrastructure that incorporates active or passive effects in addition to its intended application (Khan et al., 2021). Due to AM's ability to produce complex components without an increase in cost, engineers can structurally optimize components, using topology, to incorporate 'functional', passive effects into the infrastructure that would otherwise not be economically feasible through conventional methods (Martens et al., 2018). Examples of these passive effects include the modulation of shape, geometry, and/or materials to provide benefits in mechanical

strength, thermal properties, and acoustic dampening (Alkhalidi & Hatuqay, 2020; Valente et al., 2019).

This design flexibility offered by AM also allows designers to incorporate more efficient structures and optimize the building's energy efficiency to reduce the reliance on energy-consuming climate control systems (Alkhalidi & Hatuqay, 2020). Alkhalidi and Hatuqay (2020) demonstrated this idea in their case study regarding the energy efficiency of a 3DPC house and how differing wall dimensions and materials affected the net U-values of the structure. AM allowed Alkhalidi and Hatugay (2020) to find the optimal choice by changing the internal geometry of the exterior walls without drastically changing the construction costs or dimensions of the entire structure. These topological optimizations can also be tailored to incorporate influences from nature, as stated by du Plessis et al. (2021), who believe AM allows for a "synergy" to occur between it and biomimicry. Biomimicry is the process of learning from and emulating nature to solve engineering problems (du Plessis et al., 2021). It has been implemented to great success in structures like the Eastgate Center (Harare, Zimbabwe), which regulates its temperature through a passive thermoregulation system similar to termite mounds (du Plessis et al., 2021). Du Plessis et al. (2021) argue that AM can be used as a cost-effective way to insert similar biologically inspired features into infrastructure components to improve thermal performance, reduce resource use, and optimize structural components.

Suntharalingam et al. (2021) used 3DCP to construct lightweight concrete walls that provided significant protection and insulation from thermal energy and fire. Their study was done in multiple steps, with variations of wall thickness, internal geometry,

and insulating material. The optimal solution was selected for its ability to protect while also being economical and efficient to produce (Suntharalingam et al., 2021). Sarakinioti et al. (2018) used AM to construct a structural wall component while integrating geometries that maximized thermal insulation and heat storage, thereby creating an adaptive façade panel to control heat exchange between the interior and exterior environment. The constructed wall had two key features, the first of which was a closed cellular structure that was directionally optimized to maximize low thermal conductivity (Sarakinioti et al., 2018). Second, the wall was designed to store water that served as a pumpable heat sink, which stored and moved excess energy either away from or toward the structure depending on the season. According to Sarakinioti et al. (2018), the design is still in the proof-of-concept phase and requires further research, but AM's ability to incorporate thermal optimization makes this mono-material structure possible. Similarly, He et al. (2020) examined the effectiveness of a 3DP vertical green wall (3DVGW) at improving the thermal performance of a building's envelope and found that it provided a 10.2% reduction in annual load.

As evidenced in this section, AM has countless potential benefits that could make it an attractive choice for the construction industry. This leaves the question: *Why has the technology not been adapted yet for commercial use?* The answer to that is all too familiar because with most emerging technologies, especially one as new and complex as AM, there are numerous challenges for the engineering community to overcome. The next section will cover these major challenges, the efforts of the research community, and the progress made so far to make AM a viable option for the construction industry.

Challenges of Additive Manufacturing

As discussed earlier, the inherent difficulty with adopting new, disruptive technologies into an industry is the many obstacles that typically arise throughout the process. This section will explore the major challenges of AM found within the literature and highlight some of the recent advancements made by researchers. When researching AM in the context of its adaptation into the construction industry, many of the challenges referenced by the literature revolve around the development of new materials and practices (Nerella et al., 2020). For this reason, this section is organized into three major topics: material rheology, reinforcement strategies, and construction standards.

Material Rheology

As stated earlier, the majority of AM research for the construction industry is focused on the use of concrete as printed material. Concrete-based construction has numerous benefits stemming from the relatively low cost of OPC or comparable binders, worldwide availability, favorable material properties, and good durability (Le et al., 2012). Concrete is also well understood and adaptable via mix design to meet the specifications of the task for which it is intended. According to Song et al. (2021), the term "rheology" was coined in the 1920s and "refers to how a material deforms and flows when subjected to applied stresses and shear speeds." Using rheology, engineers can easily modify the properties of concrete by modifying things such as the cement hydration and fineness, temperature, proportions of ingredients, size and shape of the aggregate, and/or adding various admixtures (Hou et al., 2021; Song et al., 2021). Concrete mix design is an enormous field of research that has been active since the material was first used (Meurer & Classen, 2021). However, because the layer-by-layer

process of AM differs greatly from traditional methods, mix designs intended for those uses are not applicable for 3DCP (Hou et al., 2021; Panda et al., 2018). Therefore, engineers developing concrete mixtures for 3DCP must consider crucial components of rheology. These four components are Extrudability, Flowability (Pumpability), Buildability, and Open Time (Khan et al., 2020; Meurer & Classen, 2021; Valente et al., 2019). The multiple-level material design for 3DPC is shown in Figure 3.

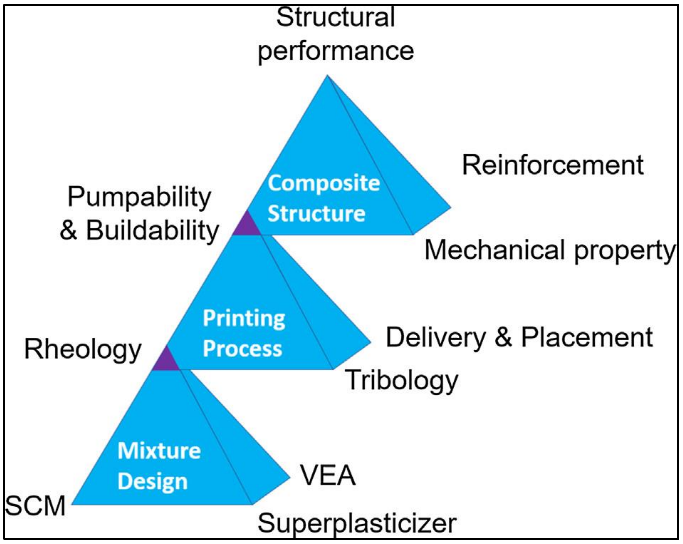


Figure 3. Multiple-Level Material Design for 3DPC (Lu et al., 2019)

"Extrudability" is defined as a material's ability to be pumped smoothly through an extruder without disruption or clogging (Panda & Tan, 2018; Valente et al., 2019). Any significant presence of tearing or splitting of the extruded filament is evidence of a material's poor extrudability (Chen et al., 2022). Le et al. (2012) note that extrudability is primarily influenced by the workability or consistency of the concrete mix proportions. Material properties such as particle size, gradation, surface area, etc., all contribute to the

flow characteristics of the material inside the extruder (Panda & Tan, 2018). In addition to the mixture, the geometry of the nozzle, extruder design, and pumping system all affect extrudability (Valente et al., 2019). Because of possible variability, three common tests are used to determine extrudability; they are the ram-extruder, penetration resistance, and vane rheometry methods (Valente et al., 2019). Chen et al. (2022) support this assertion, saying that a ram-extruder can be regarded as an extrusion model for quantifying the fresh properties of printable concrete.

A material's "flowability" or "pumpability" refers to the ability of the material to easily flow through the deposition nozzle without discontinuity (Panda & Tan, 2018). This property is also commonly referred to as slump and is tested using the traditional slump test (Valente et al., 2019). While high flowability gives the materials better extrusion characteristics, the printed material must also have enough stiffness to retain its shape until cured. Lu et al. (2019) argue that in addition to rheology, a material's tribology should also be considered as the internal material friction and friction between the hose and material contribute greatly to pumpability. J. Zhang et al. (2019) noted that adding calcium aluminate cement (CAC) to OPC was an effective means of improving both initial flowability and hardening rate (i.e., buildability).

The "buildability" of a material refers to the ability of the previously printed layers to support progressive layers above them without failure (Hou et al., 2021; Valente et al., 2019). There are two failure modes in buildability: material plastic collapse and elastic buckling failure (Chen et al., 2022). Balancing this property with flowability becomes a challenge due to the need to achieve optimal stiffness while also leaving the material liquid enough to be placed evenly. Labonnote et al. (2016) and Valente et al.

(2019) both agree that the relationship between buildability and flowability is often regarded as the most critical property because of the likelihood of structural flaws (e.g., voids) occurring when an optimal balance is not achieved. One method to quantify a material's buildability was introduced by Le (2012), who suggested quantifying the number of filament layers that could be built up without noticeable deformation of lower layers.

According to Nerella et al. (2020), the most straightforward method of assessing buildability is to produce a full-scale structure. That said, Nerella et al. (2020) explain that this is unrealistic and suggest that there are three primary parameters to consider when defining buildability tests in laboratory investigations: height of the wall, section geometry of each layer and the total number of layers to be printed, and time interval between subsequent layers. These parameters are applied by Nerella et al. (2020), who overview the importance of direct printing buildability tests as a universal standard that has not yet been accepted.

According to Valente et al. (2019), the "open time" of a material refers to the change of concrete flowability with time. Panda and Tan (2018) point out that a material's thixotropy (i.e., open time) is often equated incorrectly to its set time. It can be more accurately defined as the printability window, or the time during which all previous properties remain consistent within their tolerances (Chen et al., 2022; Panda & Tan, 2018). The duration of open time needs to be balanced to closely follow the layer printing time, as the previous layer of printed material needs to remain flowable (workable) enough to bond to the newly printed layer (Alchaar & Al-Tamimi, 2021). An open time that is too short increases the likelihood of insufficient layer bonding that

creates structural deficiencies, while an open time that is too long has the potential to negatively affect the material's buildability (Joh et al., 2020; Labonnote et al., 2016). When researching the impact of surface moisture on interlayer bonding, Sanjayan et al. (2018) discovered an interesting phenomenon where moisture would decrease at first before increasing again. This variation in moisture, attributed to evaporation and bleeding, had a dramatic effect on the potential bond strength and should be accounted for when determining the appropriate open time for the concrete mix (Sanjayan et al., 2018a).

Other challenges related to material rheology involve new material characteristics unique to 3DPC, which are the result of the AM process itself. Some of these challenges include weak interfacial bonding, poor freeze/thaw performance, and excessive shrinkage/cracking (Hou et al., 2021; Y. Zhang et al., 2019). Of these, the weak interfacial bond is potentially the biggest flaw of 3DPC, as it drastically reduces the material's strength and creates anisotropic behavior, and leads to potential delamination due to an abundance of freeze/thaw cycles or extreme temperatures (Cicione et al., 2021; Hou et al., 2021; Xia et al., 2019). In their study into reinforcement techniques, Marchment and Sanjayan (2020b) found that the average bond strength in their samples was approximately 42% of the concrete's tensile strength. Nerella et al. (2019) note that the occurrence probability of weak interfaces can be reduced through measures such as decreasing extrusion height, retaining constant flowrates and printhead velocity, and/or preparing the substrate before subsequent layers. Hosseini et al. (2019) had some success using a sulfur-black carbon polymer as a pseudo-mortar between extruded layers to improve tensile cohesion by more than 100%.

The pumping and extrusion of concrete also impart different characteristics on 3DPC, giving it 0.9% less entrapped air compared to conventionally casted concrete (Cicione et al., 2021). This reduction in porosity, while good for compressive strength, has the consequence of trapping water vapor at elevated temperatures, which increases the risk of spalling (Cicione et al., 2021). On the other side of the temperature spectrum, issues were found by Assaad et al. (2020) when studying the frost resistance of 3DPC. Results of their study showed that 3DPC was highly susceptible to frost attack due to its low porosity, even with the inclusion of an air entrapment agent (AEA). The lack of formwork, while being a huge benefit in terms of cast and waste, can also have detrimental effects on the curing rate of 3DPC. No formwork means an increased surface area is exposed, thereby increasing the evaporation rate of water and the potential for stress cracks and/or excessive shrinkage (Buswell et al., 2018; V. Li et al., 2020).

<u>Reinforcement</u>

In addition to material rheology, research for the implementation of structural reinforcement with printed components is a commonly cited challenge for AM, specifically 3DPC. The greatest weakness of using concrete as a construction material is its poor performance when it is exposed to tensile stress and flexural forces (Asprone et al., 2018; V. Li et al., 2020). In many cases, the tensile strength of concrete is not even considered in design (Asprone et al., 2018). The most prevalent method of solving this weakness of concrete is with the addition of vertical and horizontal deformed steel reinforcement, or rebar, thus creating a material known as reinforced concrete (Bester et al., 2021; Bos et al., 2016; Mechtcherine & Nerella, 2018b). However, according to De Schutter et al. (2018), the implementation of vertical steel reinforcement still has no

satisfactory solution that has been widely accepted. Yu et al. (2021) echo De Schutter et al. (2018) when noting that 3DPC has an inherent incompatibility between the extruded filament and reinforcing steel placement. Unfortunately, without a reliable means of reinforcement, 3DPC is as (or more) vulnerable to tensile forces as conventionally cast, unreinforced concrete (Khan et al., 2020). Consequently, this weakness negatively affects the amount of geometrical freedom and topological optimization offered by 3DCP (De Schutter et al., 2018).

That being said, multiple alternatives have been proposed and are currently being tested or researched. One such alternative includes reinforcement through conventional methods by only printing permanent formwork, placing rebar reinforcement, and 'infilling' the mold with conventional concrete (De Schutter et al., 2018). This method was reportedly tested by multiple WinSun and Apis Cor construction projects, but it limits the geometric freedom of the 3DP component (Ghaffar et al., 2018; Sanjayan & Nematollahi, 2019; Wu et al., 2016). HuaShang Tengda Ltd., a Chinese building company, demonstrated a novel method of printing around traditional rebar reinforcement using a special nozzle that straddled the rebar mesh and deposited extrudate on either side (Marchment & Sanjayan, 2020b). Marchment and Sanjayan (2020b) experimented with a similar technique but on a smaller scale and with wire mesh (0.5mm dia.) rather than rebar. They found that the incorporation of wire mesh reinforcement increased flexural strength by 170-290%.

One of the more common ways of reinforcement found in the literature is the inclusion of micro/nanofibers into the printable mixtures, with some notable examples being high-tensile strength steel fibers, glass fibers, polymers, and carbon (Khan et al.,

2020; Song et al., 2021; Suntharalingam et al., 2021; Weng et al., 2020). This fiber-reinforced concrete (FRC) has improved compressive, tensile, and flexural strength characteristics, but it also exhibits poorer flowability and extrudability traits (Arunothayan et al., 2020; Hou et al., 2021). FRC components are also not comparable to conventional steel bar reinforced concrete in terms of overall strength (Ma et al., 2019). One of the unique challenges associated with 3DP-FRC components is the tendency for the fibers to orient in the print direction, which magnifies the already anisotropic properties of 3DPC (Figueiredo et al., 2020; Z. Li et al., 2020a; Ma et al., 2019). Engineers can certainly take advantage of this phenomenon, but it needs to be considered when designing components and their print paths (Figueiredo et al., 2020).

3DP-FRC also fails to reinforce the interfacial bond, which again is a notable weak point of 3DCP (Hou et al., 2021). In a recent case study, Yu et al. (2021) found that their 3DP engineered cementitious composite (3DP-ECC) showed evidence of slight fiber-bridging and it was quasi-brittle. Their trials also involved groove-printing to enhance the mechanical interlock of the interface, which provided significantly higher loading capacity before delamination (Yu et al., 2021). Surprisingly, when testing a 3DP-FRC (steel) matrix, Arunothayan et al. (2020) found a significantly higher interfacial bond strength than the reported values in the literature but admitted that future research would be necessary to fully comprehend why.

Similar to 3DP-FRC, where the reinforcement is integrated into the extrusion step, wire reinforcement (WRC) methods are also researched for use in 3DCP. 3DP-WRC is accomplished through the continuous integration of a wire (typically steel) into the extruded material (Bos et al., 2017). One issue with 3DP-WRC that Bos et al. (2017)

found was that the smooth wire does not promote high bond strengths, thereby leading to more failures from pullout rather than wire breakage. In addition, as with 3DP-FRC methods, 3DP-WRC lacks the ability of layer bridging, which leaves the interfacial bond unreinforced (Bos et al., 2017). In their case study, Z. Li et al. (2020b) tested five different types of "micro-cables" (steel, nylon, carbon, aramid, and polyethylene) to analyze their reinforcement effectiveness. They found that while some cables provided up to an 83% increase in flexural strength, the weak interfacial bonds significantly affected the performance of the components (Z. Li et al., 2020b). Mechtcherine et al. (2020) sought to improve upon traditional 3DP-WRC methods by replacing the steel wire with mineral-impregnated carbon fiber (MCF). As expected, incorporation of the MCF improved flexural strength by 38% (perpendicular to bonded layers), but issues with the bonding of the MCF resulted in some failures by pullout (Mechtcherine et al., 2020).

Another method of reinforcement being explored is pre/post-tensioning of 3DPC components. Gebhard et al. (2021) state that this method is one of the most promising, as the post-tensioning tendons can adapt to the non-straight voids provided in a topologically optimized part. In combination with 3DP-FRC, this method allows for larger degrees of freedom, thus giving engineers better opportunities to utilize the optimization potential of AM to greater effect when compared with traditional rebar reinforcement (Gebhard et al., 2021). Even before the statements from Gebhard et al. (2021), Salet et al. (2018) demonstrated the effectiveness of post-tensioned reinforced 3DPC with the successful construction of a pedestrian (bicycle) bridge in Gemert, the Netherlands, that complied with all Dutch building regulations. The bridge consisted of six 3DP-WRC components combined and tensioned by 16 tendons, making a single

uniform span measuring 6.5-meter long and 3.5-meter wide (Salet et al., 2018). Later on, Vantyghem et al. (2020) successfully demonstrated the effectiveness of post-tensioning reinforcement methods in their proof-of-concept study that produced a girder with a 4-meter span. The girder also implemented topological optimization techniques that reduced material consumption by 20% (Vantyghem et al., 2020).

In a study focused on increasing the flexural and interfacial bond strength, Perrot et al. (2020) utilized the placement of nails through multiple layers of fresh 3DPC. The experiment tested multiple orientations of nail penetrations and surface finish, showing good promise as a future means of reinforcement. Perrot et al. (2020) concluded that further refinement is still needed to solve nail bonding issues, but the process could be easily automated and integrated into current extrusion-based 3DCP processes. Similar to the method from Perrot et al. (2020), Marchment and Sanjayan (2020a) studied the effectiveness of sequentially penetrating precut lengths of rebar through a predetermined amount of freshly printed layers to function as lapped vertical reinforcement. Unfortunately, the reinforcement effectiveness was not measured as its primary purpose was the study of the reinforcement's bond strength achieved at differing penetration depths, so no post-reinforcement strength measurements were taken. That said, Marchment and Sanjayan (2020a) concluded that once the issues with poor bonding strength were corrected, this reinforcement method could become an effective means of solving 3DPC's weak interfacial bond. Baz et al. (2020) found similar issues with the weak bonding strength of 3DPC to traditional rebar, albeit for different reasons. In their study, horizontally placed (before printing) rebar had significantly more void space that

contributed to 78-87% of the bonding strength of traditionally cast/vibrated samples (Baz et al., 2020).

The last method of reinforcement reviewed is arguably the most unique, as it incorporates AM techniques to print steel reinforcement bars, as shown in Figure 4. Mechtcherine et al. (2018) introduced this technique that utilizes WAAM capabilities to progressively build up vertical steel reinforcement bars in conjunction with each additional layer of 3DPC. Material testing of the printed bars exhibited a 28% lower modulus of elasticity and yield stress, 16% lower tensile strength, and 250% higher strain capacity when compared to conventional rebar. The bonding strength of the printed bars was also comparable to conventional methods, leading Mechtcherine et al. (2018) to conclude that with more testing, 3DP steel reinforcement could be a viable alternative for 3DCP. That said, one apparent issue with this method is the speed at which the reinforcement can be printed. This problem was the focus of a study from Yassin et al. (2020), who explored an optimization model for the use of 3DP steel reinforcement and 3DCP operations. This optimization model determined that the ideal ratio was 10 steel printing heads to every one concrete printer; although this resulted in a high initial cost, it provided a relatively fast return on investment when compared to conventional methods (Abou Yassin et al., 2020).

Figure 4. Examples of 3DP Steel Reinforcement Bars (Mechtcherine et al., 2018)

Construction Standards

The last major issue affecting the integration of AM into the construction industry is the lack of unified construction standards, relevant guidelines, and proposed procedures for mixture evaluation and material testing (Kazemian et al., 2017; Song et al., 2021). Meurer and Classen (2021) echo this sentiment when they state that even though AM is regarded as one of the most promising innovations for the industry, the lack of a consistent characterization methodology for assessing the behavior of 3DP-hardened material is missing, thus hindering the widespread use in engineering practice. Gebhard et al. (2021) note that 3DPC still lacks compliance with structural integrity requirements, which limits its structural applicability. Zuo et al. (2019) warn that without any early testing, blindly printing full-size buildings will likely cause accidents and losses. Yang et al. (2018) state that construction companies will have a hard time initiating 3DCP because of the high cost and no universal standard or technical system to

assist in cost estimating. Hou et al. (2021) also feel that it is of “vital necessity” to develop some universal standard for testing the printability and mechanical properties of 3DPC.

However, developing standards for a technology that is constantly evolving, and incorporating new means of reinforcement and mix design, is far from an easy task. Kazemian et al. (2019) say just as much when stating that the establishment of universal criteria will only be possible after many more studies have been carried out to produce more data on printed material performance before it is used in actual construction projects. Therefore, the new goal of Meuer and Classen’s (2021) research was to begin filling that gap with a new experimental framework for assessing flexural, tensile, shear, and compressive strength, but even they recognized that much more research is needed in the field before any given method gains wide-spread acceptance.

III. Methodology

The purpose of this chapter is to outline the methodology used to analyze the current field of construction industry-related additive manufacturing (AM) research. The first part of this methodology includes a brief introduction into science mapping and scientometrics, in addition to providing information on the various software packages used throughout this analysis. The second part of Chapter III provides an in-depth description of this research's analysis workflow to include the data-collection method, pre-processing, unit of measure selection, data layout, and data visualization. By the conclusion of this chapter, the first two investigative questions will have a clear explanation as to how they will be answered, and the third investigative question will be subjectively answered using the knowledge gained throughout this research.

Science Mapping and Scientometrics

In a research field as vast and growing at the rapid pace that AM is, it can be nearly impossible to incorporate influences and knowledge from across its spectrum to characterize its current state. It is simply too arduous a task to review thousands of published works and produce a relevant conclusion in time for them to be useful (Bos et al., 2016). Fortunately, the process of science mapping provides a unique solution to this problem. Science mapping is defined by Chen (2017) as "a generic process of domain analysis and visualization." According to Su and Lee (2010), science mapping allows researchers to conduct systematic literature discoveries by linking concepts that have been overlooked in manual reviews. Science mapping has several components, notably a

body of literature, scientometric and visual analysis tools, and metrics and indicators that highlight potentially significant patterns, trends, and theories of scientific change (Chen, 2017). Of those components, scientometrics is of great importance as it is the primary process by which this research analysis is conducted.

Scientometrics was first defined by Nalimov and Mul'chenko (1971) as developing "the quantitative methods of the research on the development of science as an informational process." More clearly, scientometrics is the quantitative study of scientific communications, which applies bibliometrics to scientific research (Börner et al., 2005). At the heart of scientometrics is the citation. Mingers and Leydesdorff (2015) refer to the citation as the core of scientometrics and as a means of "providing linkages between people, ideas, and journals and institutions to constitute an empirical field or network that can be analyzed quantitatively." This means that by using scientometrics, quantitative analysis can be conducted on massive conglomerations of data using only the citations and that subjective but relevant conclusions can be drawn regarding the data as a whole.

The most common way for analyzing the results of the quantitative portion within scientometrics is through visualizations (Pollack & Adler, 2015). Börner et al. (2005) explain "…[scientometrics provides] the graphic rendering of bibliometric data designed to provide a global view of a particular domain." It is recognized that because the quantitative results of a scientometric analysis are mostly visual, this "global view" is interpreted through the subjective lens of the researcher (Börner et al., 2005). This essentially means that the interpretation can be skewed from factors or opinions outside what is present within the data. However, scientometrics remains an effective and

efficient means of providing a holistic analysis of a given research field. Therefore, this research intends to analyze the literature related to the construction industry application of AM techniques in an attempt to answer the investigative questions posed in Chapter I.

Data Processing Software

Since a scientometric analysis requires the processing of possibly thousands of published articles, there are many tools available to assist in such a large task. These tools vary in functionality, each with its strengths and limitations. For this research, four different pieces of software were leveraged for the analysis. These packages include NVivo 11.6, VOSviewer 1.6.17, Gephi 0.9.2, and Zotero 5.0.96.3.

NVivo is a software program produced by QSR International and is used for qualitative and mixed-methods research. It is the only software package used during the research that required purchase ($99 for a 1-year student license). NVivo specializes in the analysis of unstructured text, audio, video, and image data, including interviews, focus groups, surveys, social media, and journal articles (*QSR | NVivo*, 2022). NVivo was primarily used in this research for keyword frequency analysis, cluster analysis, and trend analysis.

VOSviewer is a software tool designed for constructing and visualizing bibliometric networks, which can include journals, researchers, or individual publications (*VOSviewer*, 2022). It was created by Nees Jan van Eck and Ludo Waltman from the University of Leiden in the Netherlands and is available via free download from https://www.vosviewer.com/. VOSviewer was used during this research for data layout and visualizations of various iterations of co-occurrence network mapping.

Gephi is open-source software for network visualization and analysis, which can help analysts reveal patterns and trends, highlight outliers, and make conclusions about data (*Gephi*, 2022). It is available for free download at https://gephi.org/. Gephi was used to calculate descriptive statistics regarding network maps produced from VOSviewer.

Zotero is an open-source citation management software supported by the non-profit Roy Rosenzweig Center for History and New Media. It has multiple functions, from storing bibliometric data to the ability to organize, tag, exclude, and search references efficiently and effectively (*Zotero*, 2022). Zotero is available online for free download at https://www.zotero.org/. Zotero was used throughout this research as a citation management tool, but during the analysis it was the primary tool used for pre-processing data.

Analysis Workflow

This research is mainly structured around the workflow model presented in Börner et al. (2005), with additional influences from Chen (2017). Börner et al. (2005) introduce the six-step workflow method shown as Figure 5 to process the literature and produce visualizations for qualitative analysis. The method is described by Börner et al. (2005) as a "User-Meta Model," where the "User" first reduces the amount of literature involved via search terms, queries, or filters, and the "Meta" is the collection of authors, titles, and abstracts used to define relationships and visualizations. The six steps within the User-Meta Model are (1) data extraction, (2) unit of analysis, (3) selection of measures, (4) calculation of similarity, (5) ordination, and (6) visualization for qualitative

analysis. Börner et al. (2005) explain that steps four and five are commonly combined into a single operation termed "data layout", and as such, this research will follow suit.

DATA EXTRACTION	UNIT OF ANALYSIS	MEASURES	LAYOUT (often one code does both similarity and ordination steps)		DISPLAY
			SIMILARITY	ORDINATION	
SEARCHES	COMMON CHOICES	COUNTS/FREQUENCIES	SCALAR (unit by unit matrix)	DIMENSIONALITY REDUCTION	INTERACTION
ISI	Journal	Attributes (e.g. terms)	Direct citation	Eigenvector/ Eigenvalue solutions	Browse
INSPEC	Document	Author citations	Co-citation	Factor Analysis (FA) and Principal Components Analysis (PCA)	Pan
Eng Index	Author	Co-citations	Combined linkage	Multi-dimensional scaling (MDS)	Zoom
Medline	Term	By year	Co-word / co-term	Pathfinder networks (PFNet)	Filter
ResearchIndex			Co-classification	Self-organizing maps (SOM) includes SOM, ET-maps, etc.	Query
Patents		THRESHOLDS			Detail on demand
etc.		By counts	VECTOR (unit by attribute matrix)		
			Vector space model (words/terms)		ANALYSIS
BROADENING			Latent Semantic Analysis (words/terms) incl. Singular Value Decomp (SVD)	CLUSTER ANALYSIS	
By citation					
By terms				SCALAR	
			CORRELATION (if desired)	Triangulation	
			Pearson's R on any of above	Force-directed placement (FDP)	

Figure 5. User-Meta Model Process Flow Diagram (Börner et al., 2005)

Data Extraction

The first step in the User-Meta Model, Data Extraction, is arguably the most important. Börner et al. (2005) agree with such assessment, saying "the quality of any mapping or visualization is necessarily constrained by the quality of the underlying data." In scientometrics, the quality of the underlying data is affected by many different factors. One such factor concerns the database the literature is collected from, as it must provide comprehensive and accurate sources of citation data (Mingers & Leydesdorff, 2015). Of the databases that exist, the most commonly used ones are Web of Science (WoS), Scopus, and Google Scholar (Darko et al., 2019; Mingers & Leydesdorff, 2015).

WoS is a Clarivate (previously Thomson Reuters Institute for Scientific Information) managed citation database whose core collection contains over 21,000 scholarly journals in over 250 sciences, social sciences, and humanities disciplines dating

back to 1900 (*Clarivate | WoS*, 2022). Scopus is a "source-neutral" abstract and citation database managed by Elsevier B.V.; its collection contains over 25,800 scholarly journals across the physical, social, health, and life sciences (*Elsevier | Scopus*, 2022). Of those, its database contains over 9,000 journals linked to the physical sciences (e.g., engineering, environmental, materials science, computer science). Unlike WoS, the Scopus database only reaches back to 1995. Google Scholar works in an entirely different way than WoS or Scopus, being that it searches the Web for documents that reference books or papers rather than being a database of journals (Mingers & Leydesdorff, 2015). Consequently, the reliability and quality of Google Scholar can vary greatly; therefore, it is used much less in scientometric studies.

From these options, Scopus was chosen as the database to be used for this research. This was because Scopus is easily accessible online through the D'Azzo Research Library at the Air Force Institute of Technology. Furthermore, the Scopus database has a wide range of scientific publications, faster indexing, and more recent publications when compared to WoS (Darko et al., 2019; Hosseini et al., 2018). With the database selected, the next step was to develop the appropriate sequence of terms. This task can be a challenge to balance, as terms that are too broad or too many terms can introduce unreasonable work downstream. For this reason, it was recognized that while it is important to be comprehensive with search terms, it is equally important to be selective.

Using this philosophy, the search criteria for Scopus were "Printing" AND "Construction"; additionally, "Additive" AND "Construction" was also used. The search had no timeframe limitations, with "All Years" selected in the date range drop-down

menu; however, it was limited to just keywords, with "Keywords" selected in the search within the drop-down menu rather than "Keywords, Titles, and Abstracts". The database search was conducted on 23 November 2021, resulting in 1088 articles. The results were downloaded (exported) from Scopus with the following information categories: citation information, bibliographical information, abstract and keywords, funding details, and other information. These categories contain multiple sub-categories of information which can be found in Figure 6. In the interest of maintaining data completeness, all sub-categories were selected for this research.

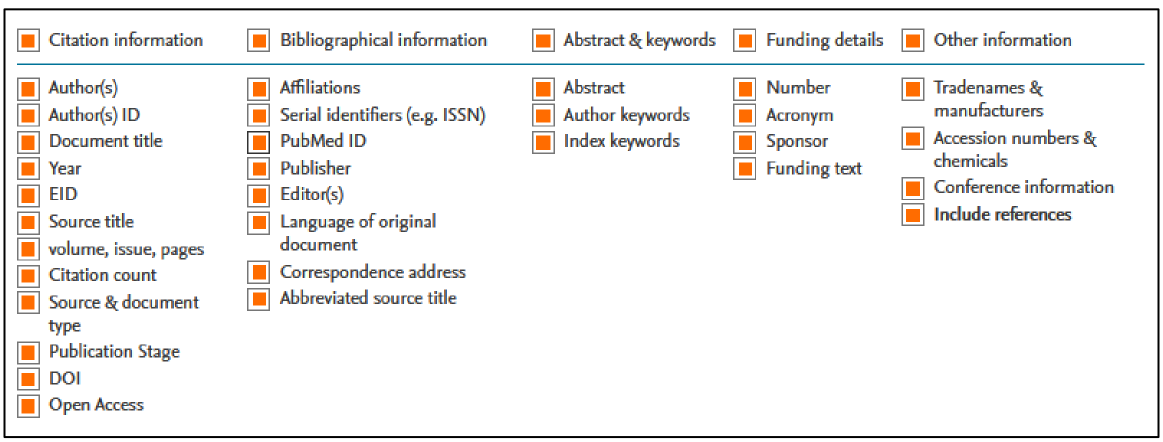


Figure 6. Scopus Export Information Selection (*Elsevier | Scopus*, 2022)

Before moving further into the User-Meta Model, time was taken to pre-process the exported Scopus data. Zotero was leveraged to accomplish this task, as its User Interface (UI) is extremely useful for efficient sorting, review, and exclusionary tasks. During this pre-processing, 505 articles were excluded with titles, abstracts, and keywords unrelated to AM and the construction industry. Furthermore, duplicate articles

and those not published in English were also removed from the data set. Of the 1088 articles exported from Scopus, 8 were found to be duplicated, and 53 did not contain abstracts. However, of the records not containing abstracts, only two had titles that hinted at a possible relation to the AM research field. The small number of records only accounts for 0.38% of the exported data, so its exclusion was determined to have negligible impacts on any conclusions made. The resulting bibliometric data was reduced from 1088 articles to 522.

Unit of Analysis

The second step in the User-Meta Model is the selection of a unit of analysis. According to Börner et al. (2005), this unit should be relevant to the questions one desires to answer. For this research, there were no limitations placed on the document type retrieved from Scopus, which is recognized as breaking from conventional practice. Hosseinni et al. (2018) explains that non-journal articles such as conference papers are published in such large numbers that they do not typically provide much new information and only introduce unnecessary complications to the analysis. This point is shared by Santos et al. (2017) who state that for science mapping purposes, utilizing articles found in highly-ranked scholarly journals sufficiently represents the bulk of influential research studies, thereby making a qualitative analysis possible. However, the inclusion of conference papers into this research data was deliberate. This was done because conference papers may not require the completion of a study to be published but might represent the leading edge and direction of research.

The most common units used in the science mapping of literature are journals, documents, authors, and descriptive terms or keywords (Börner et al., 2005). Yet the

analysis of an entire journal article or document can be arduous. It can also be unproductive since the results can be skewed through an author's repetitious writing. Therefore, science mapping research traditionally focuses on the text used by the authors themselves to describe their work, which are the title, abstract, and chosen keywords (Pollack & Adler, 2015). Of these, the article title is often rejected as a unit of analysis because the purpose of titles is to grab the attention of the reader rather than provide a complete summary of the work within (Pollack & Adler, 2015). Pollack and Adler (2015) also recognize potential flaws with the other two metrics, of which most are the result of a given publisher's requirements. For example, some publishers may require that authors pick keywords from a pre-determined list, meaning that the appropriate terms may be absent in the final document. Abstracts can also be limited by certain publisher requirements. Yet, the aggregation of abstracts and chosen keywords still represents the best and most concise synopsis of a given article's content (Darko et al., 2019; Pollack & Adler, 2015). For this reason, the scientometric analysis conducted here focused on the abstracts and chosen keywords.

Selection of Measures

An important step of the data analysis portion of scientometrics is the selection of measures. Selecting the appropriate measure provides the resulting qualitative analysis with sufficient context to make appropriate conclusions about the topic in question. The measures can also vary based on what analysis or visualization is required. For this research, there were four separate measures: keyword co-occurrence, network mapping, network descriptive statistics, and trend analysis. Each of these was used for a different portion of the data manipulation, analysis, and visualization.

The first part of the scientometric analysis sought to gain insight into the breadth of construction industry-oriented AM research. Keyword co-occurrence was selected because it is a widely accepted means of offering a good picture of the domain and provides context on the coverage of topics, their associations, and organizations (Darko et al., 2019). Su and Lee (2010) argue that "keywords represent the core research of a paper." Furthermore, White and McCain (1998) define the "co-" relationship as "implying joint occurrences within a single document…Co-citation occurs when any two works appear in the references of a third work… 'co-' relationships are explicit and potentially countable by computer…yield[ing] raw data for visualization of literature."

NVivo was used to conduct the frequency count of keywords and those within the abstracts. The threshold value (measurement) was set to 100 words, meaning that NVivo would return the 100 most frequently used words found within the keywords and abstracts of the data. NVivo initially defaults to 1000 words when selecting the "Word Frequency Query." This was scaled down to 100 as a means of simplifying the computations and analysis, while also maintaining the breadth required to support the conclusion made when answering the investigative questions.

When utilizing VOSviewer to construct the network, density, and time-based mapping visualizations, a different threshold was required. That is because VOSviewer differs from NVivo in the way it excludes terms and is based on a minimum occurrence value before being sorted 1 through N. Therefore, the threshold for VOSviewer was determined to be 10, meaning a given term was required to occur a minimum of 10 times to be included in the analysis. This threshold resulted in 102 keywords, which was then reduced to 100 as a means of staying consistent.

With the wider breadth of research data analyzed, another iteration of keyword co-occurrence was conducted to narrow the focus and discover the key areas of AM research. To do this, VOSviewer was leveraged once again, but with the addition of Gephi to calculate descriptive statistics for the network nodes. To create this narrower scope, a threshold of ~40 keywords was preferred. This threshold was not hard-set for the same reasons as before, meaning the number of keywords is dependent on the minimum occurrence value. Yet, with the minimum occurrence set to 20, only 39 keywords met the criteria, but this was deemed sufficiently close to the desired 40.

The last part of the scientometric analysis utilized trend analysis to explore the evolution of the research over time. Using NVivo, the threshold value was set to 20, as the top 20 most frequently occurring words were plotted for each year. Each year would then be merged to provide a visualization of how the research has developed since its first inception.

Data Layout

Following the acquisition of data, selection of units, and pre-processing steps, the data was then subjected to multiple iterations of scientometric analysis. This analysis contained the following four definitive blocks.

1. Keyword Co-Occurrence (NVivo)
2. Network Mapping (VOSviewer)
3. Focused Network Descriptive Statistics
4. Trend Analysis

As stated earlier, the purpose of the first analysis block was to provide the information required to make a proper conclusion regarding the scope of construction industry-related

AM research. The knowledge gained during this block, and later during Block 2, represents the primary stepping stones to answer Investigative Question 1. For this reason, Block 1 utilized NVivo to determine keyword co-occurrence and then produce a 2D cluster map and horizontal dendrogram.

Using NVivo's "Word Frequency Query," the top 100 most frequently used words (abstracts and keywords) within the given 522 articles were determined. One important option to consider when setting up this type of query in NVivo is the minimum word length and "Grouping" option. As shown in Figure 7, all queries conducted during this research used the following options. The minimum word length was set to 4 to reduce inconsequential words such as "the", and the "Grouping" option was set to include "stemmed" words. Börner et al. (2005) suggest that researchers used stemmed words to reduce the number of unique terms, thereby providing a cleaner and more accurate analysis. The use of "stop words" was also leveraged to reduce the impact of commonly used words in the English language and eliminate any word related to the base search terms "additive", "print", and "construct". The complete list of "stop words" is shown as Appendix A.

The resulting data can be presented in different ways, with the first being a detailed summary containing a list of words, their count, and weighted percentages. A 2D cluster map and horizontal dendrogram were also produced using NVivo. The cluster map displays the 100 keywords as differently sized orbs within a circular field. The size of each keyword's respective orb is related to its occurrence total throughout the research; proximity to other keywords and similarity in color are indicators of correlation between the terms. These correlations are more clearly displayed in the horizontal

dendrogram, which provides clear lines to indicate separate clusters and the correlations between the 100 terms.

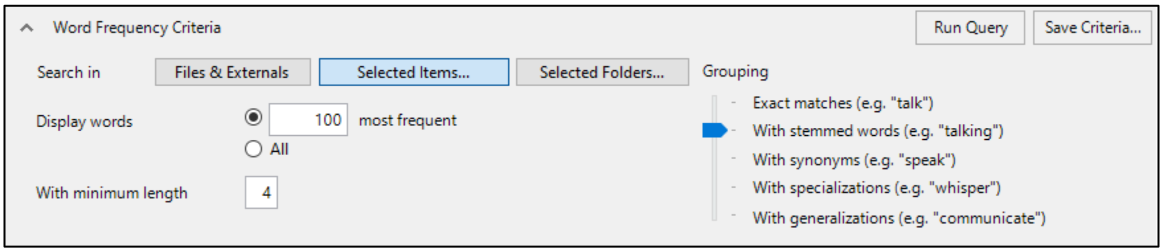


Figure 7. NVivo Word Frequency Query Criteria

Block 2 of the analysis expands on the information analyzed in Block 1 but utilizes VOSviewer to produce the visualizations for analysis, which are based on the top 100 most frequently used words in the abstracts and keywords of the given 522 articles. As shown in Figure 8, "Fractional Counting" was selected as the counting method for all analyses done by VOSviewer, Fractional counting means that the link is fractionalized; an example would be that if an author co-authors a document with 10 others, then each co-authorship link is weighted as 1/10 (*VOSviewer*, 2022). This was done in keeping with similar scientometric studies from Darko et al. (2019) and Hosseini et al. (2018). VOSviewer does not require the user to determine a "Grouping" option like NVivo, as its internal code accounts for those types of similarities. Furthermore, VOSviewer contains an internal list of "stop words" which is not user-adjustable; therefore, manual filtering was used to eliminate words related to the base search terms "additive", "print", and "construct", as shown in Figure 8.

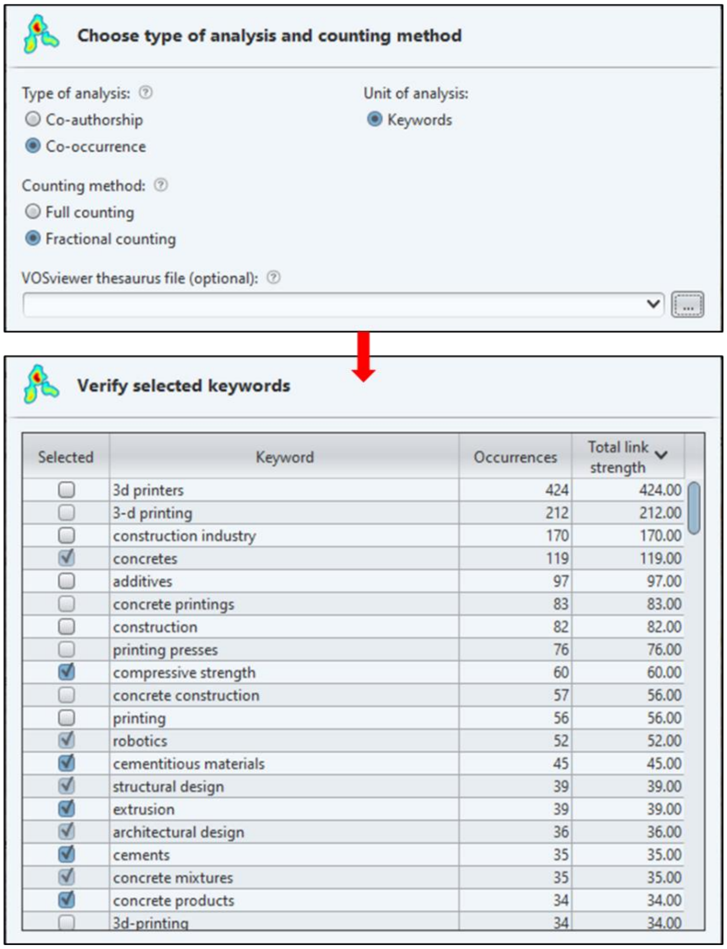


Figure 8. VOSviewer Network Mapping (VOSviewer 2022)

The Block 2 visualizations produced using VOSviewer were network mapping, density mapping, and time-based mapping of the top 100 terms. Network mapping is presented similarly to the 2D cluster analysis of NVivo, but the differently sized nodes are interconnected by edges. As with the 2D cluster, the size of the node is proportional to the frequency of the term. VOSviewer also clusters the nodes using the same color scale as NVivo. The edges tell a different story, where the distance between connected nodes represents the strength of correlation between the two. The farther away the nodes are the less correlation they share, and vice versa (*VOSviewer*, 2022). Time-based

mapping differs only slightly from the methodology used in network mapping, as the color now represents clusters based on the average year that the term was most frequently used. Lastly, density mapping displays the data as progressively lighter patches of color on a neutral background, with the less frequent terms becoming almost transparent. The size of the text used is also representative of the term's frequency.

In Block 3, the goal was to provide focused visualizations to allow for accurate answers for the first part of Investigative Question 2. Therefore, the same VOSviewer analysis from Block 2 was conducted, but with the top 40 terms. The resulting network was then exported to Gephi, which was used to calculate descriptive statistics for the network. The most important statistic is the measurement of a node's degree of centrality. Darko et al. (2019) reference Prell (2012), who states that measuring the centrality of nodes is the most reliable and simplest method to recognize what is important in a network. Calculating the importance of each node based on the number of links it shares is an excellent way to understand its influence on the wider topic (Darko et al., 2019). Influence is represented by the degree as a number; the bigger it is, the more influence the term has. The weighted degree was also an important statistic calculated by Gephi, as ties between terms with equal degrees are broken by which one has the higher weighted degree (Darko et al., 2019). The final descriptive statistic calculated was the Eigenvector Centrality, which is another way of measuring the influence of a given node. According to Golbeck (2013), "Eigenvector centrality measures a node's importance while considering the importance of its neighbors." That said, eigenvector centrality is interpreted just like degree, where the higher the value, the more influential the node is.

In the last block of analysis, NVivo was used once again to extract the top 20 most frequently used words. However, this time the data was segregated by publication year. The reason for this segregation was to produce a dataset that would represent word usage trends over time. Microsoft Excel was used to combine each year's top 20 terms and produce the trend charts required for qualitative analysis. This dataset was primarily used to answer the final part of Investigative Question 2.

Data Visualizations

The previous section went into many of the unique visualizations produced during each block of analysis. Each of these visualizations is crucial in providing the best information for the qualitative analysis of the research, which is as follows.

- Block 1 (Produced by NVivo)
    a) Frequency Count Table of Top-100 Terms
    b) 2D Cluster Map & Horizontal Dendrogram of Top-100 Terms

- Block 2 (Produced by VOSviewer)
    a) Network, Density, & Time-Based Mapping of Top-100 Terms

- Block 3 (Produced by VOSviewer & Gephi)
    a) Network, Density, & Time-Based Mapping of Top-40 Terms
    b) Descriptive Statistic Table of Top-40 Terms

- Block 4 (Produced by NVivo & Excel)
    a) Trend Analysis Table of Top-20 Terms Per Year
    b) Trend Analysis Charts of Top-20 Terms Per Year (Selective)

Using subjective reasoning, experience, and knowledge gained throughout this research process, the visualizations are analyzed and conclusions are drawn. The next chapter, Analysis and Results, includes those interpretations and conclusions resulting from these visualizations.

IV. Analysis and Results

This chapter contains the results of the science mapping analysis methodology described in Chapter III. The first part will provide the results of an overview of the literature by relevant descriptive statistics which include article type and publication year, top journal and conference paper publications, top authors, and most cited articles. This portion is referred to as bibliometric analysis herein, as its focus is predominately on the literature as a whole and similar to the traditional science mapping methodology of bibliometric analysis (Darko et al., 2019; Hosseini et al., 2018). The chapter also includes the results of the scientometric analysis, in addition to the resulting interpretations and discussion of the qualitative and quantitative methods. The goal of this chapter is to explore the past and present trends of the research related to additive manufacturing (AM) in the construction industry to provide clear answers to the investigative questions.

Descriptive Statistics of Data

This section contains the results of a bibliometric analysis of the literature sourced from the Scopus database on 23 November 2021. As stated in Chapter III, the search criteria used were “Printing” AND “Construction”; additionally, “Additive” AND “Construction” were also used. The search also included all article types (e.g., journal, conference paper, etc.) and was limited to “All Years”. The bibliometric analysis of this data includes the following descriptive statistics: article type and publication year

distributions, top 10 journal and top 5 conference publications, top authors, and top 20 most cited articles.

Article Type Distribution

The distribution of articles by type was determined, as the search criteria did not restrict the results to only journal articles. The resulting distribution is shown in Table 1, with the overall count and percentages shown for each article type. As shown in the table, the majority of data sourced from the Scopus consisted of journal articles, accounting for just over 68% of the total. The remaining data consisted primarily of conference papers, at 31.2%. Lastly, data from books was almost negligible, at 0.5%. Figure 9 provides a visual display of the article type distribution.

Table 1. Distribution of Sourced Articles by Type

Article Type	Count	Percentage
Journal Article	356	68.20%
Conference Paper	163	31.23%
Book	3	0.57%
Total	**522**	**100%**

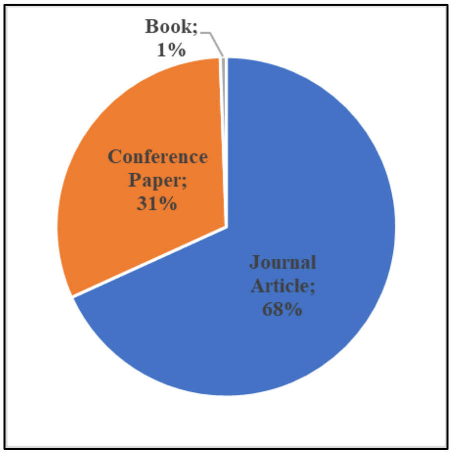


Figure 9. Visual Distribution of Sourced Articles by Type

Publication Year Distribution

In addition to the various types of data sourced from Scopus, the search was not constrained by year, which is an uncommon practice as it typically would result in large amounts of data. However, because AM is still a relatively new technology, the time range of relevant research is inherently limited to the past ~30 years. Figure 10 displays the distribution of AM-specific articles based on publication date and the normalized results using the total number of published articles within the "Physical Science" field of Scopus. In the figure, there is a significant increase in the number of articles published after 2015. This trend indicates an exponential increase in construction industry-related AM research during recent years, which has been noted by multiple researchers (e.g., Nemotollahi et al. (2017) and Romdhane et al. (2020)). Three articles were dated 2022, even though the data was sourced in 2021. This is the result of the articles being present within Scopus, but earmarked for journal publications beginning in 2022.

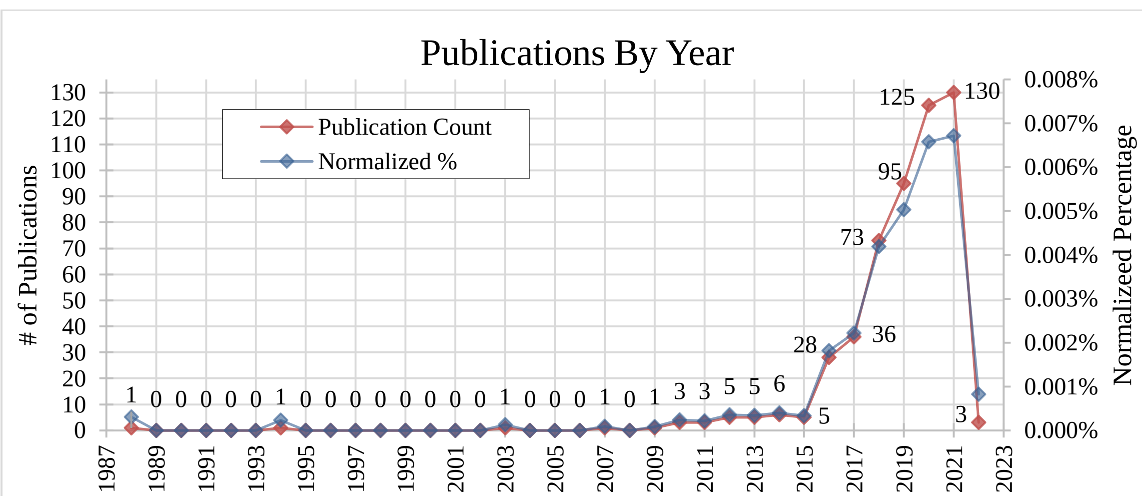


Figure 10. Distribution of Sourced Articles by Published Year

Top 10 Journal Publications

It was found that the articles were distributed across many different journals. Table 2 displays the top 10 journals, which are rank-ordered by the number of articles attributed to them. Of these top journals, which are all associated with the construction industry, "Constr. and Building Materials" occupies the top spot with 37 articles. Table 2 also displays each publication's Impact Factor (IF), which is a metric of influence based on citation data. Of these top 10 journals, 9 have an IF greater than 3, which is representative of a good publication. "Concrete & Rein. Concrete Constr." is the only publication with an IF below 3, but this is most likely due to it being in German. A total of 145 articles were found in these journals, accounting for 40.7% of the journal articles sourced from the Scopus database. This percentage is evidence of the wide distribution of journals from which the journal articles were sourced, providing the benefit of many different perspectives rather than that from a few influential publications.

Table 2. Top 10 Sourced Journal Publications

Rank	Journal Publication	Count	Impact Factor	Percentage
1	Construction and Building Materials	37	6.141	10.39%
2	Materials	21	3.623	5.90%
3	Automation in Construction	20	7.700	5.62%
4	Additive Manufacturing	17	10.998	4.78%
5	Cement and Concrete Composites	10	7.586	2.81%
6(T)	Cement and Concrete Research	9	10.933	2.53%
6(T)	Journal of Cleaner Production	9	9.297	2.53%
8	Materials and Structures	8	3.428	2.25%
9(T)	Sustainability (Switzerland)	7	3.251	1.97%
9(T)	Concrete & Reinforced Concrete Constr. (DE)	7	1.198	1.97%
	Total	**145**	**6.863 (Med.)**	**40.73%**

Top 5 Conference Paper Publications

Like the journal articles, the sourced conference papers were also found to have come from a wide distribution of conferences. This was so apparent in the data that determining a top 10 was nearly impossible; therefore, the top 5 conference paper publications are shown in Table 3. Interestingly, the “International Symposium on Automation and Robotics in Construction” (ISARC) provided 23 papers, accounting for over 14% of the sourced conference papers. However, the ISARC total includes papers from various years whereas the “International Association for Shell and Spatial Structures Symposium” (IASS) provided six papers from 2019 alone. Looking back at Table 3, it is reasonable to assume that IASS Symposium 2020 would have had more papers but, unfortunately, the COVID-19 pandemic postponed the event for the year. Another interesting point from Table 3 is that the International Astronautical Congress occupies the 4th spot with eight papers, which is evidence of the interest in AM construction from the space community.

Table 3. Top 5 Conference Paper Publications

Rank	Conference Title	Count	Percentage
1	ISARC (Various Years)	23	14.11%
2	Intl. Conference on Progress in AM	11	6.75%
3	IOP Conf. Series: Materials Science & Engr.	10	6.13%
4	Intl. Astronautical Congress (IAC)	8	4.91%
5	IASS Symposium, 2019	6	3.68%
	Total	**163**	**35.58%**

Ranking Authors by Total Publications

The distribution of journal authors was also found to vary greatly across the dataset with 344 unique records, but there were some reoccurring names. Table 4 shows the ranking of 46 journal article authors with two or more articles in which they were cited as the primary contributor. The table also contains the H-index of the top 12 authors, which is representative of an author's scholarly output and performance. Analysis of the table shows that most authors (34) have only two articles to their name, with another 11 having 3-5 articles; V. Mechtcherine led the field with 10 articles. As with previous inferences made, this distribution shows that the research field has many diverse contributors, thus providing a wider research perspective and content. Lastly, no conclusions were drawn from the H-index, as the scores do not appear to be correlated to the author's ranking in Table 4.

Using the list of authors from Table 4, the number of times each author was cited in other articles was found and added to their current primary contribution total. This revised list is shown below in Table 5, which displays the ranking authors by primary and "secondary" contributions. The addition of secondary works significantly increased the total contributions of some authors while others were found not to have any other works. V.N. Nerella and V. Mechtcherine were found to have the greatest amount of secondary works, with 13 and 11, respectively. Alternatively, just under half of the 34 authors from Table 4, were still showing only two articles to their names in Table 5.

Table 4. Ranking Journal Article Authors by Primary Contribution

Rank	Author	Count
1	Mechtcherine, V. (50)	10
2 (2)	Panda, B. (27); Xia, M. (13)	5
4 (2)	Lim, S. (11); Nerella, V.N. (19)	4
6 (7)	Gomaa, M. (5); Guimarães, A.S. (10); Kloft, H. (10); Lowke, D. (14); Ma, G. (56); Perrot, A. (25); Zhu, B. (5)	3
13 (34)	Baz, B.; Bong, S.H.; Bos, F.P.; Chaves Figueiredo, S.; Craveiro, F.; Ge, J.; Glagolev, E.S.; Hack, N.; Hoffman, M.; Kazemian, A.; Kontovourkis, O.; Kreiger, E.L.; Lafhaj, Z.; Le, T.T.; Li, Z.; Lu, B.; Marchment, T.; Muthukrishnan, S.; Nematollahi, B.; Paul, S.C.; Pierre, A.; Poluektova, V.A.; Shahzad, Q.; Shakor, P.; Suntharalingam, T.; Tahmasebinia, F.; Tay, Y.W.D.; Troemner, M.; Van Der Putten, J.; Weng, Y.; Wi, K.; Wu, P.; Xiao, J.; Zhang, J.	2
Total	**46 Unique Authors**	**117**
Key:	Last Name, First Initial (H-Index)	

Table 5: Ranking Journal Article Authors by Total Contribution

Rank	Author	Count
1	Mechtcherine, V. (50)	21
2	Nerella, V.N. (19)	17
3(3)	Xia, M. (13); Lowke, D. (14); Nematollahi, B.	10
6(2)	Panda, B. (27); Paul, S.C.	9
8	Ma, G. (56)	8
9(5)	Perrot, A. (25); Bos, F.P.; Hack, N.; Tay, Y.W.D.; Xiao, J.	7
14(2)	Lim, S. (11); Kloft, H. (10)	6
16(2)	Pierre, A.; Weng, Y.	5
18(4)	Gomaa, M. (5); Guimarães, A.S. (10); Hoffman, M.; Li, Z.	4
22(9)	Zhu, B. (5); Bong, S.H.; Kazemian, A.; Kreiger, E.L.; Lafhaj, Z.; Le, T.T.; Marchment, T.; Wi, K.; Zhang, J.	3
31(16)	Baz, B.; Chaves Figueiredo, S.; Craveiro, F.; Ge, J.; Glagolev, E.S.; Kontovourkis, O.; Lu, B.; Muthukrishnan, S.; Poluektova, V.A.; Shahzad, Q.; Shakor, P.; Suntharalingam, T.; Tahmasebinia, F.; Troemner, M.; Van Der Putten, J.; Wu, P.	2
Key:	Last Name, First Initial (H-Index)	

Top 20 Most Cited Articles

Table 6 displays the top 20 most cited articles from the sourced dataset. These articles represent the most influential and insightful voices within the research field,

which allows for inferences to be made regarding the scope of the research field in its entirety. That said, it is interesting that a third of the articles are reviews of the research. One reason for this large number of reviews could be that construction-related AM research has been growing exponentially and reviews from even one year ago are already out-of-date. It would be an insightful research topic to explore how the citation counts of the older articles change over time with the introduction of newer, more up-to-date information. Aside from the review articles, the next most common topic found in Table 6 relates to material research. This topic encompasses articles such as “Mix Design and Fresh Properties for High-Performance Printing Concrete” by Le et al. (2012), who tackle the challenge of balancing the four key rheological properties (Extrudability, Flowability, Buildability, Open Time) of 3DPC to create a model bench in a proof-of-concept experiment.

There are also multiple articles related to the effects of 3DPC’s poor interlayer bond, which was a notable weakness discussed in Chapter II. One of these articles, “Anisotropic Mechanical Performance of 3DP-FR Sustainable Construction Material” by Panda et al. (2017), explores the effects of glass fibers on a 3DPC’s flexural and tensile strength, finding that it can be greatly improved. With this conclusion, it is understandable that this article would make the top 20 list, as the weakened material properties of 3DPC when compared to conventional cast can limit its ability to serve as a suitable replacement. Another interesting point to note from Table 6 is the presence of the article “Metal 3DP in Construction: A Review of Methods, Research, Applications, Opportunities, and Challenges” by Buchanan and Gardner (2019). This inclusion reinforces the idea that not all AM applications in the construction industry are limited to

a ceramic-based system. Buchanan and Gardner (2019) demonstrate this notion by reviewing the multiple ways that 3D metal printing has been theoretically applied to construction-related tasks, with the MX3D bridge being the most influential.

Table 6. Top 20 Most Cited Journal Articles

Rank	Article (Authors)	Journal	Count
1	Developments In Construction-Scale Additive Manufacturing Processes (Lim et al., 2012)	Automation in Construction	479
2	Mix Design And Fresh Properties For High-Performance Printing Concrete (Le, Austin, Lim, Buswell, Gibb, et al., 2012)	Materials and Structures	403
3	Additive Manufacturing Of Concrete In Construction: Potentials And Challenges Of 3D Concrete Printing (F. Bos et al., 2016)	Virtual and Physical Prototyping	387
4	3D Printing Using Concrete Extrusion: A Roadmap For Research (Buswell et al., 2018)	Cement and Concrete Research	364
5	Building Components For An Outpost On The Lunar Soil By Means Of A Novel 3D Printing Technology (Cesaretti et al., 2014)	Acta Astronautica	353
6	Hardened Properties Of High-Performance Printing Concrete (Le, Austin, Lim, Buswell, Law, et al., 2012)	Cement and Concrete Research	344
7	A Critical Review Of The Use Of 3-D Printing In The Construction Industry (Wu et al., 2016)	Automation in Construction	337
8	Structural Built-Up Of Cement-Based Materials Used For 3D-Printing Extrusion Techniques (Perrot et al., 2016)	Materials and Structures (2016)	327
9	3D Printing Trends In Building And Construction Industry: A Review (Tay et al., 2017)	Virtual and Physical Prototyping	266
10	Cementitious Materials For Construction-Scale 3D Printing: Laboratory Testing Of Fresh Printing Mixture (Kazemian et al., 2017)	Construction and Building Materials	232
11	Additive Construction: State-Of-The-Art, Challenges And Opportunities (Labonnote et al., 2016)	Automation in Construction	209
12	Anisotropic Mechanical Performance Of 3D Printed Fiber Reinforced Sustainable Construction Material (Panda et al., 2017)	Materials Letters	197
13	Fresh And Hardened Properties Of 3D Printable Cementitious Materials For Building And Construction (Paul et al., 2018)	Archives of Civil and Mech. Engineering	190
14	Measurement Of Tensile Bond Strength Of 3D Printed Geopolymer Mortar (Panda, Paul, et al., 2018)	Meas.: J. Int. Meas. Confed.	168
15	3D Printing Of Buildings And Building Components As The Future Of Sustainable Construction? (Hager et al., 2016)	Procedia Engineering	163
16	Effect Of Surface Moisture On Inter-Layer Strength Of 3D Printed Concrete (Sanjayan et al., 2018b)	Construction and Building Materials	151
17	Mechanical Properties Of Structures 3D Printed With Cementitious Powders (Feng et al., 2015)	Construction and Building Materials	150
18	Method Of Formulating Geopolymer For 3D Printing For Construction Applications (Xia & Sanjayan, 2016)	Materials and Design	150
19	Metal 3D Printing In Construction: A Review Of Methods, Research, Applications, Opportunities And Challenges (Buchanan & Gardner, 2019)	Engineering Structures	147
20	Particle-Bed 3D Printing In Concrete Construction – Possibilities And Challenges (Lowke et al., 2018)	Cement and Concrete Research	137

The last observation made from Table 6 is that there is not one singularly obvious publication that dominates the top 20 list. Again, this notion is good for the research field, as many perspectives and opinions are being shared across the subject. This

inherently drives competition amongst researchers, who then push the technological bounds of AM, which provides the field with breakthroughs that are progressing the technology closer to implementation.

Scientometric Analysis Results

This section contains the results of a scientometric analysis of the literature sourced from the Scopus database. The analysis is performed in four definitive blocks: word frequency query of the top 100 terms, network diagrams of top 100 terms, network diagrams and descriptive statistics of top 40 terms, and trend analysis of top 20 terms per year. In addition to the results, this section also includes related interpretations and discussion of the qualitative and quantitative methods.

Word Frequency Analysis

In this first part of the scientometric analysis, a word frequency analysis was conducted using the NVivo software. This analysis compared the sourced abstracts and keywords of the 522 articles within the dataset to rank the top 100 most frequently used terms, as shown in Table 7. Top words such as “materials”, “concrete”, and “reinforcing” provide important clues to the main focus of the construction-related AM research field.

Table 7. Top 100 Most Frequently Occurring Words

Rank	Word	Cnt	Rank	Word	Cnt	Rank	Word	Cnt	Rank	Word	Cnt
1	concretes	1553	26	products	334	51	requires	186	76	complex	139
2	materials	1299	27	model	330	52	unsupported	186	77	steel	139
3	structures	948	28	cements	330	53	extrusion	184	78	surface	138
4	technology	858	29	performed	327	54	dimensional	182	79	walls	138
5	industry	741	30	times	298	55	components	172	80	future	136
6	design	711	31	automation	284	56	large	169	81	possible	135
7	process	707	32	engineers	278	57	challenges	166	82	comparing	134
8	builds	701	33	compressive	268	58	efficiently	164	83	formwork	132
9	manufacturing	617	34	architectural	262	59	improve	160	84	demonstration	131
10	printers	604	35	fabrication	251	60	works	159	85	field	126
11	development	588	36	control	239	61	including	155	86	fiber	125
12	content	565	37	digitally	237	62	mortar	155	87	symposium	123
13	strengths	551	38	scaling	236	63	project	153	88	well	123
14	imported	525	39	cost	236	64	reduced	152	89	bond	121
15	methods	447	40	potential	223	65	shape	151	90	specimens	121
16	properties	446	41	composite	223	66	conventional	151	91	tensile	121
17	robots	442	42	techniques	222	67	integrity	149	92	deposits	118
18	systems	416	43	sustainable	221	68	experimental	147	93	hardening	117
19	reinforcing	394	44	high	221	69	energy	146	94	geopolymer	115
20	tests	377	45	mixtures	221	70	optimizing	144	95	objects	115
21	international	363	46	code	214	71	directly	143	96	quality	113
22	research	359	47	cementitious	203	72	environmental	142	97	fresh	112
23	applications	353	48	computing	196	73	limits	142	98	proceedings	112
24	layers	347	49	rheological	195	74	printable	141	99	loads	111
25	mechanization	339	50	elements	193	75	currently	140	100	extrudability	111

In addition to exploring the frequency of words, which alone may not be entirely useful for providing conclusive results, the relationships between terms are explored using the NVivo software. The first attempt at exploring these inter-term relationships was through the 2D cluster map shown in Figure 11. The cluster map is read in two ways. First, the size of an orb represents the term's frequency; for example, the node "concretes" is significantly larger than node "loads" because "concretes" occurs 1,442 more times than "loads". The second way to read the cluster map is the orb color, which signifies a relationship; for example, the same "concretes" and "loads" orbs, are different colors, which indicates they belong to different clusters. Unfortunately, this figure is admittedly not the most productive tool for determining clustered relationships, as solely using color differentiation can be vague and difficult to efficiently interpret.

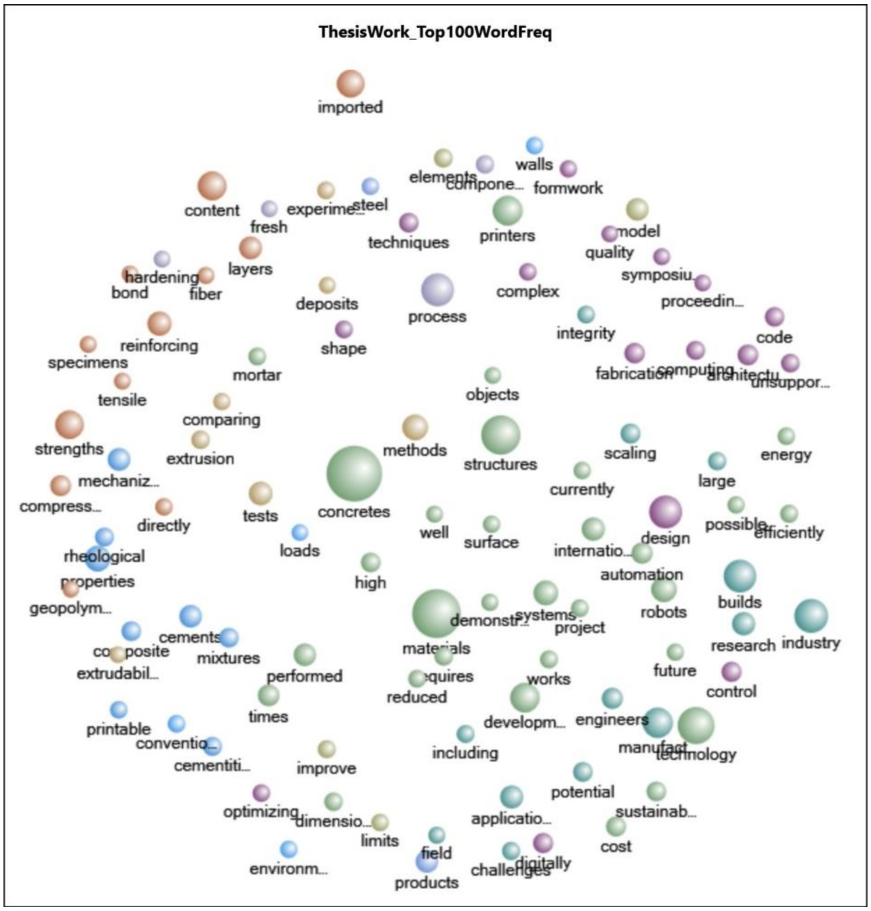


Figure 11. 2D Cluster Map for Top 100 Most Frequently Occurring Words

These interpretation challenges, demanded the use of another method to display the inter-term relationships. The resulting dendrogram, constructed using the NVivo software, is shown in Appendix B due to its size. In the dendrogram, the top 100 words are broken up into 10 clusters, with each cluster displaying a relationship between its included terms. Table 8 provides an overview of the terms and their respective clusters. A review of the table leads to multiple observations, including that the top five clusters are related to material properties of 3DPC, the four rheological properties, and alternative methods. The bottom five clusters are related more to process control, the benefits and

challenges of AM technology, LCAs, and reinforcement techniques. No major conclusions can be drawn from the dendrogram, and the inter-term relationships will continue to be explored further in this research.

Table 8. Top 100 Most Frequently Occurring Words and Clusters

Cluster	Terms
1	products, steel
2	Composite, cementitious, printable, mixtures, rheological, cements, properties, mechanization
3	model, elements, improve, limits
4	hardening, fresh, process, components
5	experimental, deposits, extrusion, extrudability, comparing, methods, tests
6	integrity, builds, potential, challenges, including, scaling, large, research, engineers, industry, manufacturing, applications, field
7	conventional, environmental, walls, loads
8	content, imported, reinforcing, fiber, directly, geopolymer, strengths, compressive, layers, bond, specimens, tensile
9	times, cost, performed, high, concretes, structures, possible, technology, currently, future, automation, robots, international, well, surface, demonstration, reduced, materials, requires, development, works, systems, project, sustainable, efficiently, energy, printers, dimensional, mortar, objects
10	control, quality, digitally, design, architectural, computing, techniques, shape, optimizing, symposium, proceedings, code, unsupported, complex, fabrication, formwork

Network, Density, and Time-Based Mapping, Top 100

While the inter-term relationships between the top 100 most frequently used words were briefly explored using the horizontal dendrogram, VOSviewer software provides much more productive diagrams to interpret those relationships. In Figure 12, those relationships are shown utilizing color similarity and a physical link. Furthermore, like the 2D cluster map in NVivo, the orbs found in Figure 12 are related to that word's overall frequency within the sourced dataset. The resulting network map contains five clusters, each with a varying number of terms associated with them.

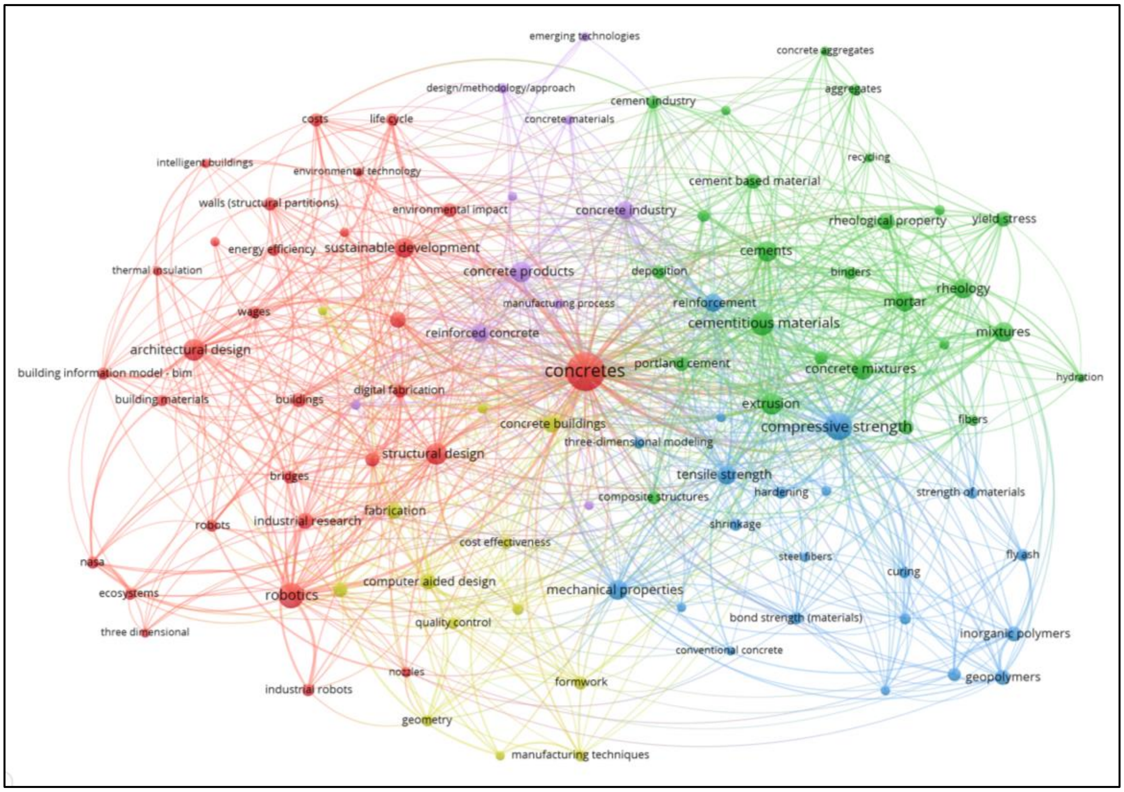


Figure 12. Network Mapping Diagram for Top 100 Most Frequently Occurring Words

The density map found in Figure 13 displays an alternative means of assessing inter-term relationships within the network. Predictably, the highest concentration (density) is found in the central area around “concretes”. The rest of the surrounding area is relatively consistent, with slight hot spots around the terms such as “robotics”, “compressive strength”, and “rheology”; however, this is not indicative of a trend over the lifespan of the sourced database.

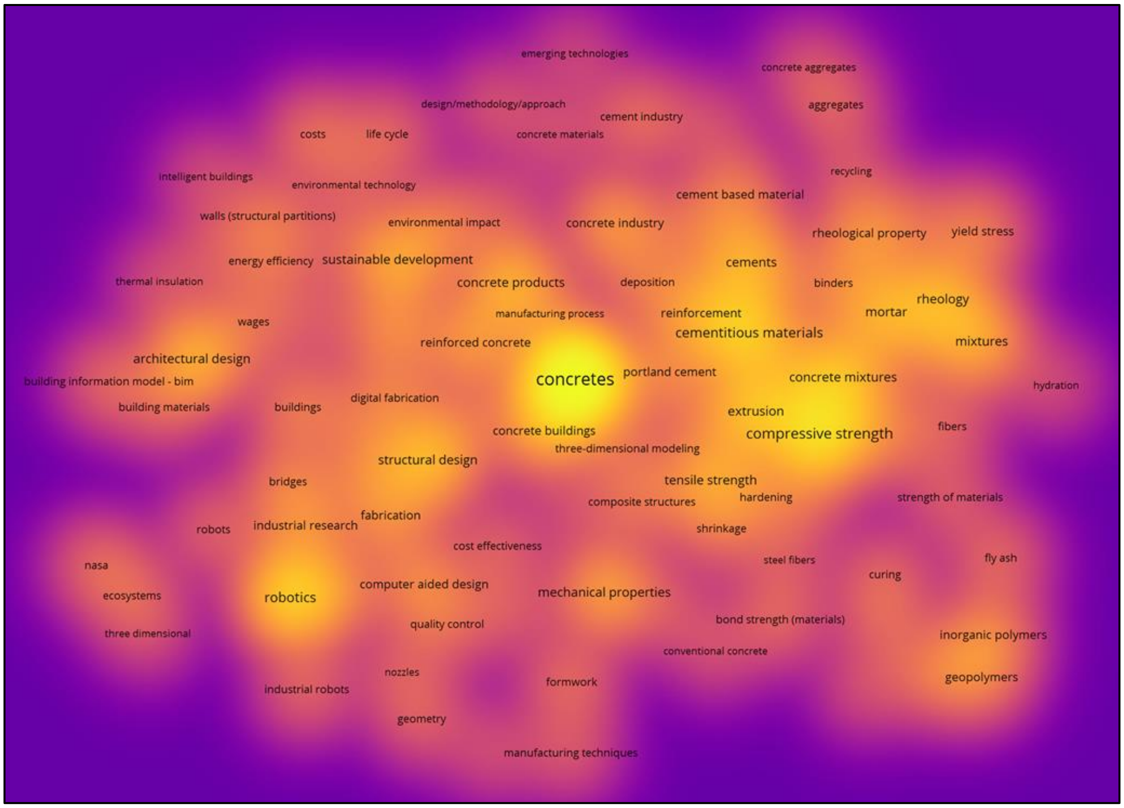


Figure 13. Density Mapping Diagram for Top 100 Most Frequently Occurring Words

The final method used within VOSviewer to display the inter-term relationships of the sourced dataset was the time-series network. This diagram, shown in Figure 14, foregoes the use of colors to differentiate between clusters; instead, it uses a colormap to display the point of time (average) when that given term was most commonly used. The time-series element of the diagram allows for inferences to be made regarding larger trends in the data. For example, “quality control” has an average citation year of around 2018, leading to the likely assertion that research since then has not been focused much on quality control measures with AM. Alternatively, “environmental impact” has a much

more recent average citation timeline of 2020, meaning that it is a recently discussed/explored topic with AM.

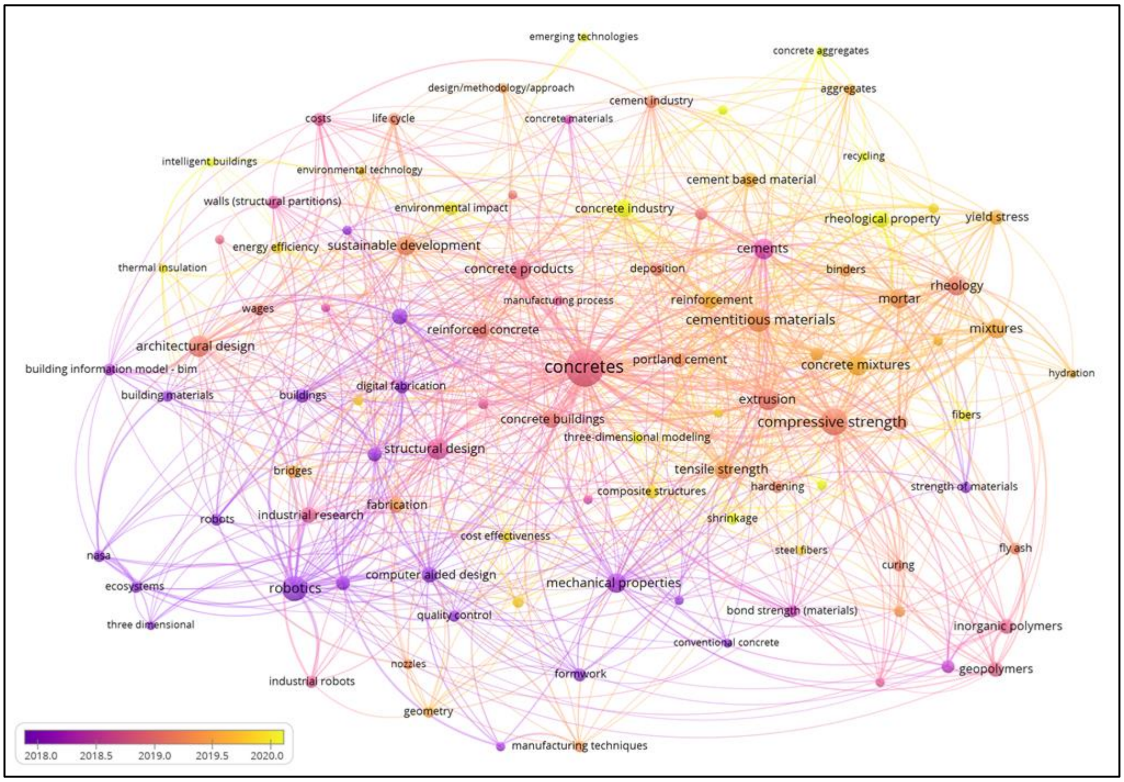


Figure 14. Time-Series Diagram for Top 100 Most Frequently Occurring Words

Network, Density, and Time-Based Mapping – Top 40

Similar to the previous analysis, VOSviewer was used to create network, density, and time-based mapping diagrams for a smaller range of words. The concept behind this analysis was to eliminate the majority of the "clutter" found within a standard top 100 network diagram, thus allowing for a better focus to be brought on key terms within the research field. Figure 15 shows the network mapping of the top 40 terms most frequently used in the sourced articles' abstract and keywords.

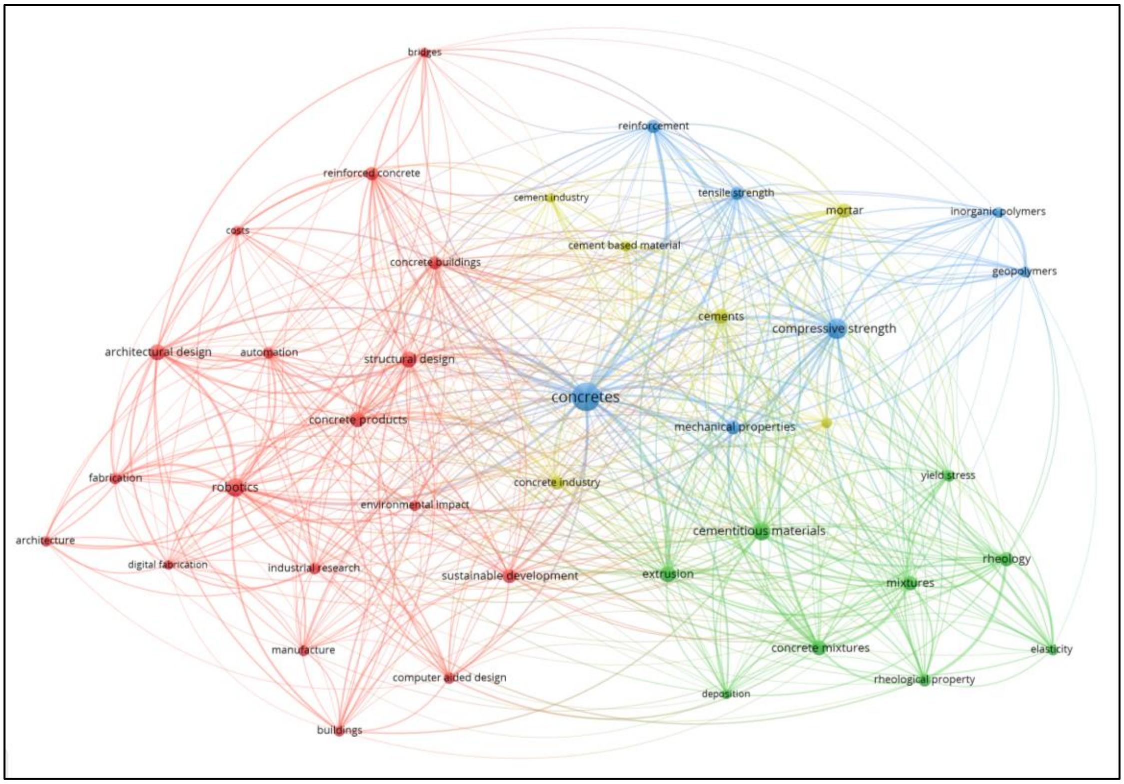


Figure 15. Network Mapping Diagram for Top 40 Most Frequently Occurring Words

The relationships associated with differing colors, orb size, and term proximity are the same as found in Figure 12. However, the reduction in overall terms provides a clearer picture of the clusters within the network. Of the four clusters in the diagram, the largest cluster is red and contains 18 terms, the largest being “robotics”. Other terms within this cluster, such as “structural design”, “architectural design”, and “concrete products”, are related to the implementation processes of AM, so the relationship with “robotics” makes sense.

Like the previous assessment, a density map diagram was also produced showing the top 40 terms from the sourced data. This diagram is shown in Figure 16 and provides similar conclusions to the previous top 40 network diagram (Fig. 15) and top 100 density

diagram (Fig. 13). However, the separation between terms like "concretes", "robotics", and "compressive strength" becomes more apparent in this density diagram when compared to the one in Figure 13. Additionally, "concretes" maintains the highest density amongst the terms, which is consistent with the previous density diagram.

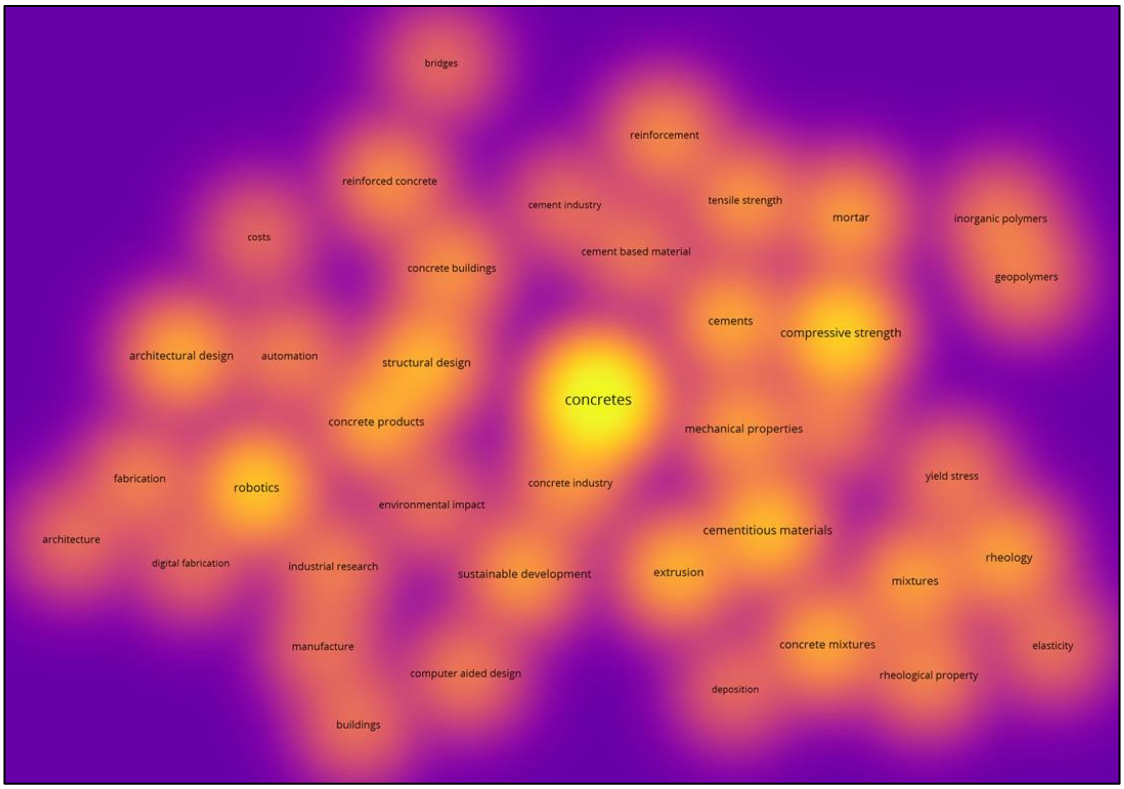


Figure 16. Density Mapping Diagram for Top 40 Most Frequently Occurring Words

The last diagram produced using VOSviewer software was a time-series mapping diagram of the top 40 terms. This diagram, displayed in Figure 17, shows the relationship between terms, using proximity and physical connections, while also color-coding them based on the average time that they were most frequently used. The same conclusions made during the analysis of Figure 14 can be made here, but this diagram

provides a more efficient means of finding possible indicators of patterns. One such indicator is that the “digital fabrication”, “robotics”, and “computer-aided design” clusters occurred before 2018. It can be inferred then that these terms do not limit AM’s adoption for construction applications. In contrast, terms such as “rheological property”, “concrete mixtures”, and “reinforcement” are frequently used terms in recently published literature. It can be inferred then that these factors are now of greater importance to the research community because they pose the greatest challenges and/or advantages of the technology.

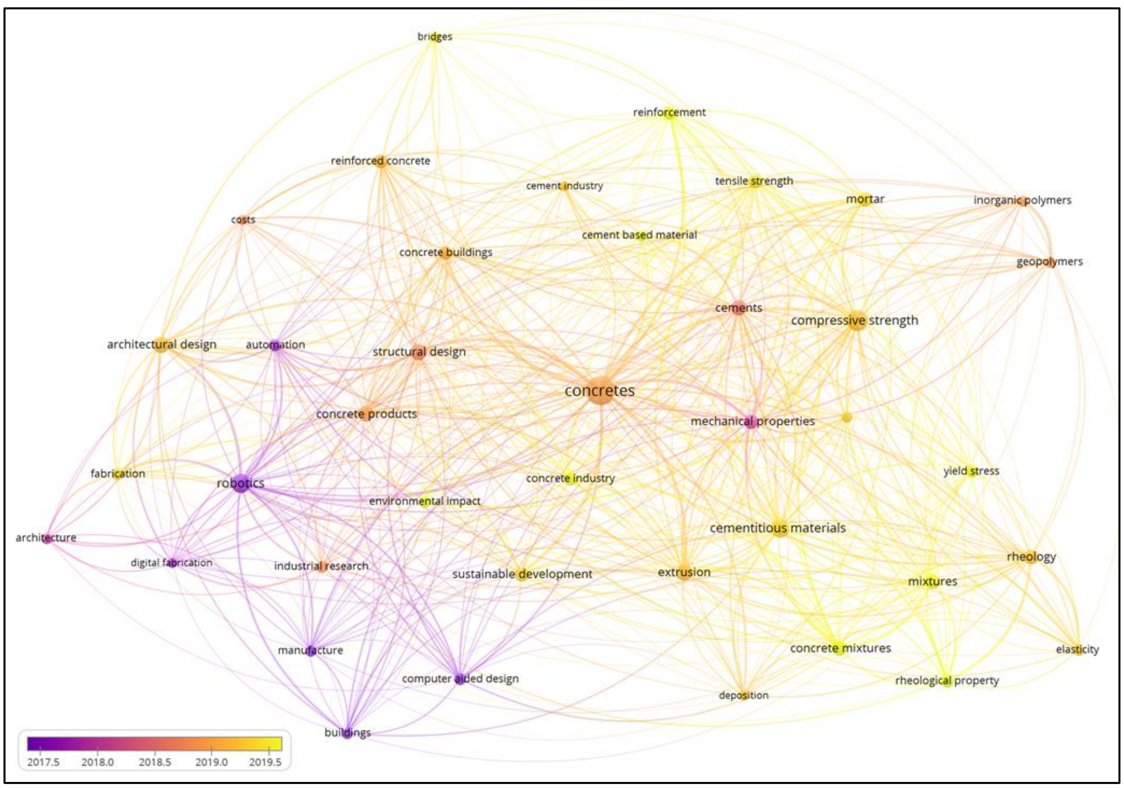


Figure 17. Time-Series Diagram for Top 40 Most Frequently Occurring Words

In conjunction with the qualitative methods used to analyze the networks produced by VOSviewer, quantitative methods were also employed to determine the importance of each node (term). According to Darko et al. (2019), the simplest and most reliable method of identifying the importance of a node is to calculate its degree of centrality (DoC). Table 9 contains the list of nodes from the network produced from VOSviewer. The nodes are ranked by their respective DoC, which was calculated using the Gephi software. DoC represents the total number of links a given node has with other nodes in the network; the more links a node has, the higher its DoC and corresponding importance to the network. As an example, the node "concretes" has a DoC of 39, meaning that it has links to 39 other nodes within the network. In a network of 40 nodes, a DoC of 39 is the maximum degree attainable, thereby indicating the node's importance to the network.

The table also includes each node's weighted degree and eigenvalue. Weighted degree (WD) is a modified way of calculating a node's DoC since it accounts for the average mean sum of strength for all links within the network (Darko et al., 2019). Weighted degree is used to break ties between nodes with equal degrees. Alternatively, the eigenvalue is another metric used to determine the importance of a given node within the network. According to Prell (2012), the eigenvalue accounts for not only the importance of the node but its importance in relation to its immediate neighbors. That said, DoC was the primary means of ranking and analysis, with Eigenvalue simply being calculated to provide perspective on an alternative method.

Table 9. Network DoC for Top 40 Most Frequently Occurring Words

Rank	Term	DoC	WD	Eigenvalue	Rank	Term	DoC	WD	Eigenvalue
1	concretes	39	103	0.084	21	cement industry	27	15	0.007
2	concrete products	36	34	0.067	22	concrete buildings	26	27	0.021
3	compressive strength	35	55	0.025	23	rheological property	26	22	0.550
4	structural design	35	34	0.835	24	portland cement	26	18	0.445
5	robotics	32	42	0.688	25	architectural design	25	34	0.000
6	extrusion	32	38	0.134	26	yield stress	24	18	0.918
7	cementitious materials	31	40	0.012	27	cement based material	24	18	0.003
8	reinforcement	31	23	0.528	28	automation	23	18	0.003
9	concrete mixtures	30	35	0.047	29	manufacture	23	14	0.216
10	cements	30	34	0.014	30	inorganic polymers	22	18	0.153
11	mortar	30	30	0.324	31	geopolymers	22	18	0.129
12	tensile strength	30	27	0.988	32	fabrication	22	17	0.158
13	sustainable develop.	30	25	1.000	33	buildings	22	16	0.004
14	mixtures	29	31	0.325	34	computer aided design	21	18	0.013
15	concrete industry	29	26	0.030	35	elasticity	21	17	0.100
16	rheology	28	32	0.664	36	environmental impact	20	15	0.108
17	industrial research	28	18	0.185	37	digital fabrication	20	15	0.091
18	mechanical properties	27	26	0.271	38	costs	17	12	0.076
19	reinforced concrete	27	23	0.298	39	bridges	16	12	0.001
20	deposition	27	15	0.087	40	architecture	11	10	0.001

Trend Analysis (2011-Present) – Top 20

The final component of the scientometric analysis encompassed a trend analysis of the last 12 years of sourced data, from 2011 to 2022. To accomplish this, the top 20 terms from each year were selected using the NVivo software. The time period from 2011 to 2022 was selected because 2011 was one of the earliest years where consistent articles were being published from then to the present day (Fig. 10). The inclusion of articles published in 2022 was also deliberate, but with the recognition that the results were not going to be considered in subsequent trend analysis plots.

Table 10 shows the compilation of the top 20 terms from 2011 to 2022. A review of this table shows that most terms such as “material”, “concrete”, and “structures”, are present throughout the 2011-2022 period. That said, even these terms are absent in some years, notably during the earlier years (before 2017). These absences could be explained

by the relatively low number of published articles during that timeframe, which may lead to the skewness of the results. Unfortunately, confirmation of this is admittedly difficult due to the extensive amount of data present.

To simplify the interpretation of possible trends, select terms were analyzed on an individual basis to better understand the changes in AM research. These terms were "material", "concrete", "reinforcement", "structures", "architectural", and "strength". Figures 18-23, display the individual trend plots for each of these terms. The trends were determined in two different ways; the first was a simple count of each year's frequency and the second normalized the occurrences by the total number of terms counted that year. This normalization was done to remove the influence of an increasing article count, which can falsely represent trends. Linear trend lines were also fitted to the plots, to assist in the visualization of a possible increase or decrease in a term's frequency.

Figure 18, shows the first of the individual trend analysis plots, starting with the term "material". As seen in the plot, the use of "material" increases over time, which is expected to happen with the increase in articles after 2016. The normalization plot better represents the trend of the use of "material", which is shown to consistently reside between 1.5-2.0%. The frequency of use appears to be stable; however, the fitted trend line displays a positive slope. Either way, "material" is a very common term within AM research, hinting at its continued importance to the future of the technology. Similar to the "material" term, Figure 19 displays a post-2015 upward trend in usage frequency for the term "concrete". However, this trend is primarily due to the increased article count, as the normalized plot provides evidence of a very slight decrease in frequency.

Table 10. Top 20 Most Frequently Used Terms, (2011-Present)

Yr	2011		2012		2013		2014		2015		2016	
Rank	**Term**	**Cnt**	**Term**	**Cnt**	**Term**	**Cnt**	**Term**	**Cnt**	**Term**	**Cnt**	**Term**	**Cnt**
1	concrete	19	concrete	23	systems	23	building	14	structures	11	buildings	72
2	components	12	manufacturing	18	technology	14	concrete	14	printers	10	technology	65
3	buildings	10	strength	18	automated	12	system	13	design	9	materials	62
4	architectural	7	layers	13	models	10	automation	11	industry	9	design	61
5	process	7	process	13	structures	10	manufacturing	11	manufacturing	9	manufacturing	59
6	digital	6	materials	13	design	9	technology	11	students	9	concrete	56
7	materials	6	components	9	industry	9	production	10	development	8	process	50
8	computer	5	properties	9	architecture	8	components	9	process	8	industry	41
9	manufacturing	5	architectural	8	building	8	method	9	new	7	structural	40
10	research	5	polymer	7	space	8	process	9	fabrication	7	products	38
11	design	5	structural	7	research	7	design	8	materials	7	printers	37
12	developed	4	high	7	robotics	7	engineering	8	technology	7	robotics	34
13	freeform	4	mix	7	nasa	6	scale	8	content	5	model	32
14	industry	4	performance	7	prototypes	6	structures	8	engineering	5	developments	30
15	performance	4	bond	6	content	5	potential	7	imported	5	architectural	28
16	state	4	mortar	6	developed	5	prototyping	7	rapid	5	content	28
17	strength	4	mpa	6	imported	5	pumping	7	stress	5	imported	28
18	symposium	4	scale	6	international	5	regolith	7	workshop	5	international	27
19	aided	3	water	6	rapid	5	content	6	architectural	5	layer	24
20	automation	3	build	5	sinterhab	5	fabrication	6	computing	5	systems	24

Yr	2017		2018		2019		2020		2021		2022	
Rank	**Term**	**Cnt**	**Term**	**Cnt**	**Term**	**Cnt**	**Term**	**Cnt**	**Term**	**Cnt**	**Term**	**Cnt**
1	concrete	183	concrete	209	structures	250	concrete	410	concrete	397	structural	10
2	materials	149	materials	176	materials	249	material	298	materials	328	design	7
3	systems	103	technology	125	concrete	228	structures	221	technology	222	habitat	7
4	robots	92	process	103	technology	145	industry	180	structural	212	martian	6
5	technology	86	buildings	102	process	145	process	177	design	193	architectural	5
6	buildings	73	structural	97	industry	138	technology	170	industry	186	engineers	5
7	development	72	robots	95	design	129	manufacturing	143	buildings	164	space	5
8	structures	72	industry	94	manufacturing	121	printers	142	strengths	159	ceramic	4
9	industry	62	printers	92	printers	118	design	137	printers	151	mars	4
10	international	60	strength	90	content	110	reinforcement	137	properties	146	models	4
11	process	58	design	89	development	110	strengths	136	content	142	processing	4
12	control	57	developments	79	buildings	108	development	134	manufacturing	135	surface	4
13	automation	53	properties	78	methods	104	content	130	imported	130	building	3
14	design	52	content	77	international	104	imported	125	development	129	challenge	3
15	manufacturing	50	imported	73	strengths	97	buildings	124	process	127	content	3
16	space	50	layer	70	imported	95	tests	111	reinforcing	119	documentation	3
17	methods	48	international	67	robots	81	methods	105	test	107	focuses	3
18	printers	41	manufacturing	58	tests	71	model	96	performed	100	geometry	3
19	content	38	cement	57	applications	70	properties	95	applications	99	humans	3
20	engineers	38	applications	52	mechanical	70	mechanical	92	methods	98	imported	3

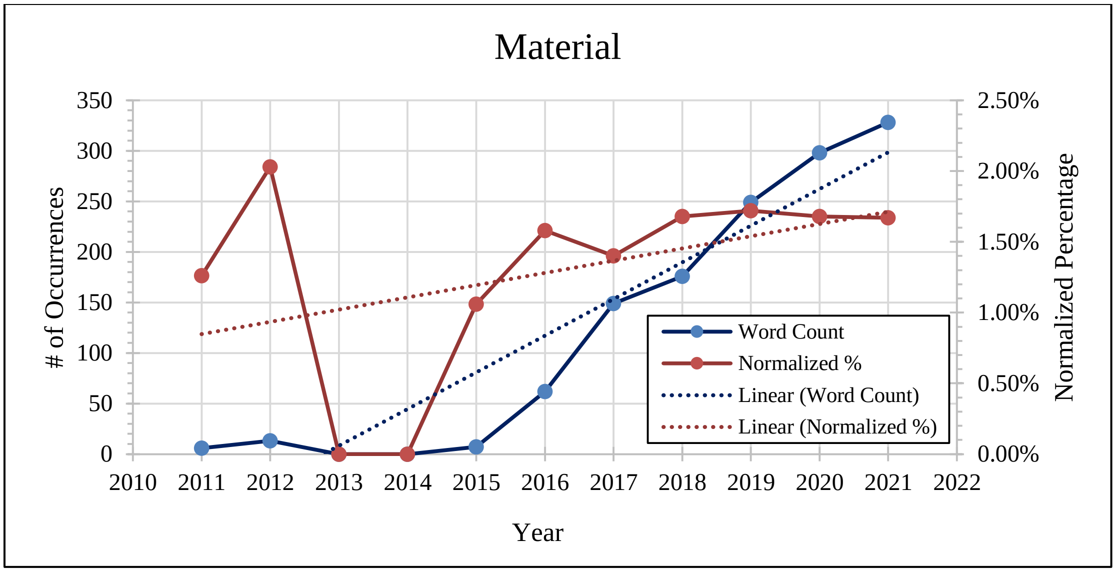


Figure 18. Term Trend Analysis for Material

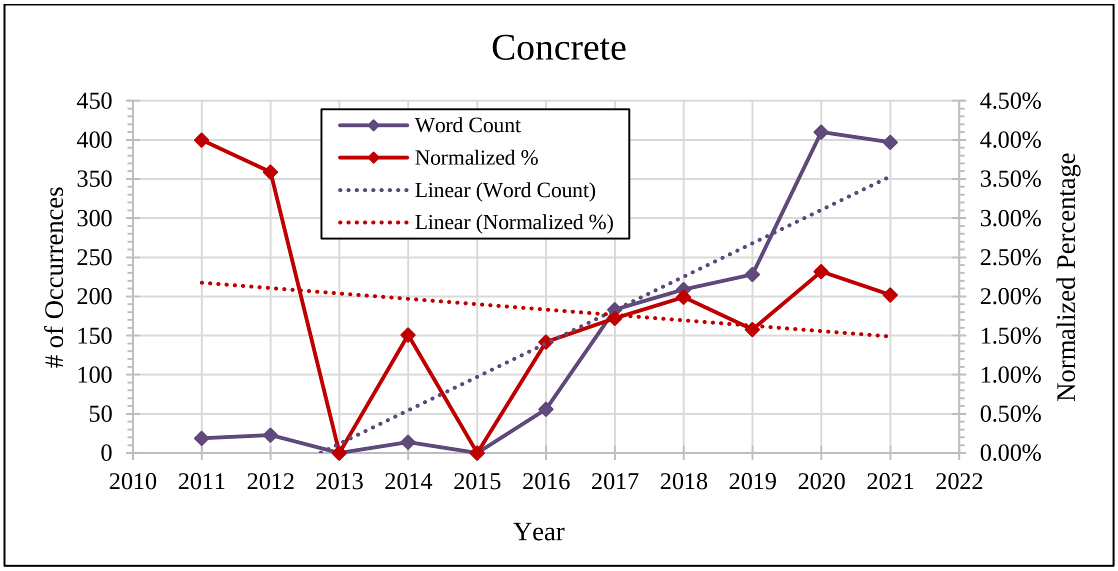


Figure 19. Term Trend Analysis for Concrete

Figure 20 contains the trend analysis plot for the term "reinforcement", which is surprisingly non-existent amongst the top 20 terms before 2019. That said, its frequency dramatically increased during 2020 before appearing to have stabilized in 2021. This

obvious increase in usage can be attributed to the drastic increase in research towards the reinforcement of 3DPC and the new technologies being developed for it. Alternatively, this increase could be invalid as the plot only contains two datapoints, thereby requiring more data to make accurate inferences on the usage trend of “reinforcement”.

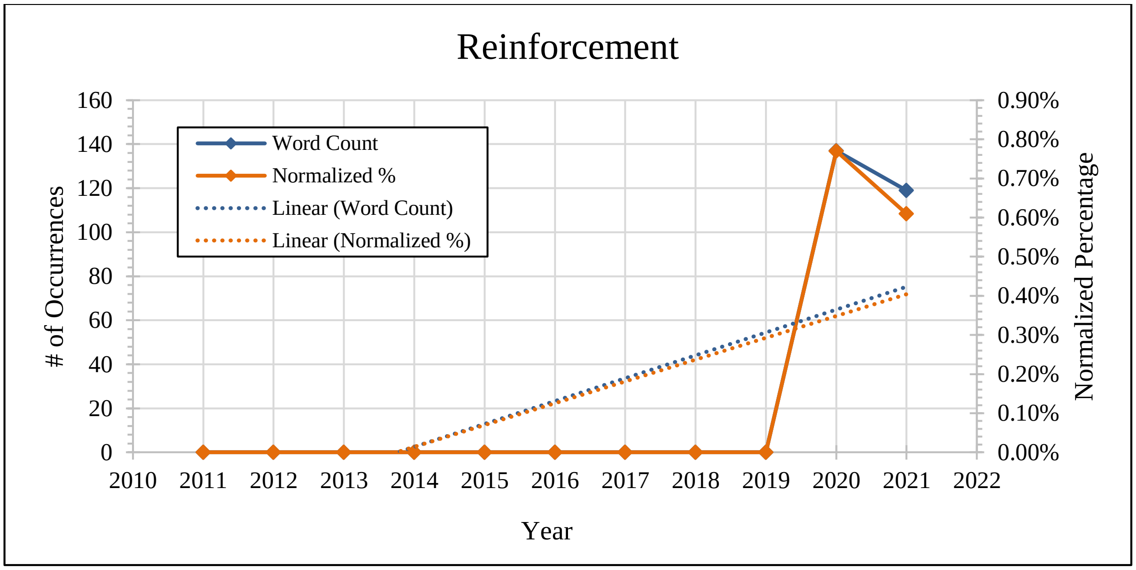


Figure 20. Term Trend Analysis for Reinforcement

“Structures” was the next term reviewed during the trend analysis, with its plot being shown in Figure 21. Unsurprisingly, this plot displays the expected increase in usage after 2015. The normalized plot also showed some evidence of an increase in the term’s usage frequency. Therefore, it was determined that more AM research is being attributed to the structural properties of 3DP materials. This increase in structural research is crucial to solving the main material properties issues of 3DPC, chief among them being the anisotropic properties of the layer-by-layer construction.

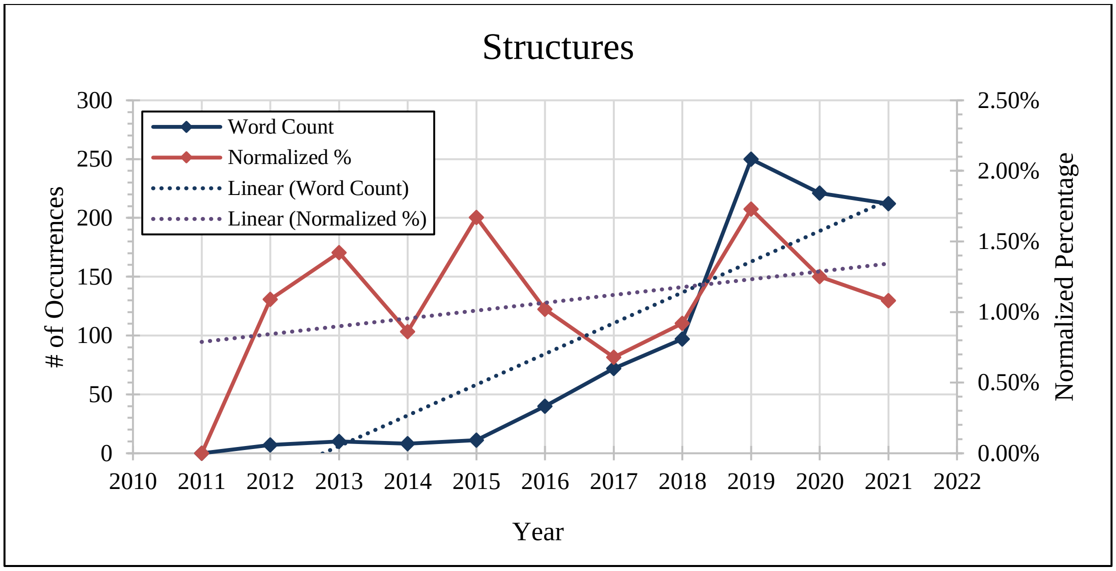


Figure 21. Term Trend Analysis for Structures

Figure 22 displays the individual trend analysis plot for the term “architectural”. Observation of the plot reveals a surprising trend, which is that the frequency of usage is falling over time. This is unique because the number of articles is increasing so it is reasonable to assume that this would also lead to increased use of the term. However, this does not seem to be the case for “architectural”, which essentially disappeared following 2016, most likely because the focus of the research changed. This change would be in the form of transitioning AM from a technology that constructed complex architecture to one that could replace conventional in-situ techniques. The decreased use of the “architectural” term and the increased use of the “structures” term supports this conclusion.

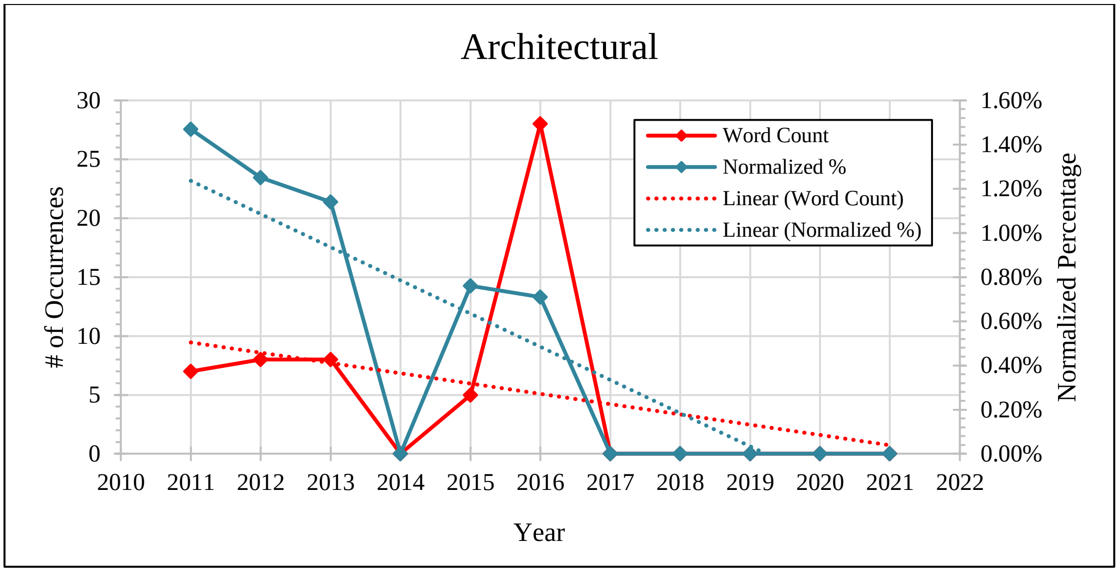


Figure 22. Term Trend Analysis for Architectural

The final individual trend analysis plot is found in Figure 23, which shows the frequency trend for the term "strength". "Strength" was selected as a term because of its relation to the material and reinforcement terms. This relation is further reflected in the similarity of the trend plots, where the frequency of "strength" increases after 2016, but not at a significant rate to infer that research efforts are increasingly concerned about it.

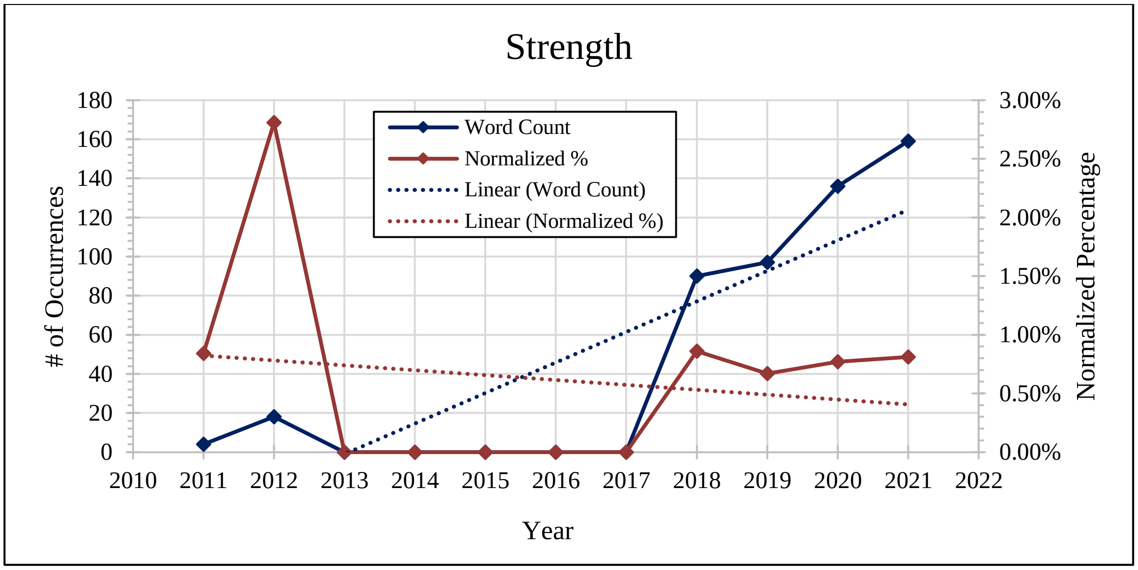


Figure 23. Term Trend Analysis for Strength

Summary

In this chapter, both qualitative and quantitative analysis of the sourced data was conducted to provide answers to the investigative questions. Specifically, the first part of the chapter explored in-depth, descriptive characteristics of the data to better understand the current state of the construction-related AM research field and thus answer Investigative Question 1. Furthermore, the second part of the chapter conducted scientometric methods of analysis to uncover key areas of focus and recent trends in the research field, thereby enabling the answering of Investigative Question 2. In the next chapter, the answers to Investigative Question 3 will be discussed as these are based on the knowledge gained throughout the research and the subjective assessment of it to develop an informed opinion on the future of AM technology in the DoD. The following chapter will also include conclusions from the results of the literature review and research, as well as recommendations for future research efforts into the AM field.

V. Conclusions and Recommendations

In this research, a scientometric analysis was conducted on literature related to the implementation of additive manufacturing (AM) technology within the construction industry. The purpose of this study was to answer three investigative questions that were presented in Chapter I. In Chapter II, a literature review was presented to provide the theoretical and technical groundwork on which this research was based. Chapter III went on to describe the science mapping and scientometric methodologies used to conduct the study; the results of which were presented in Chapter IV, which also included some observations regarding the data. In this chapter, the conclusions of the researcher will be provided, in addition to explanations on the significance of this research and recommendations for further studies into related fields.

Conclusions of Bibliometric Analysis

The results of the bibliometric analysis revealed that the majority (93.9%) of the sourced articles were from after 2015, which was determined to be indicative of the cited "exponential increase" of construction industry-related AM research (e.g., Nemotollahi et al. (2017) and Romdhane et al. (2020)). The distribution of the articles was also found to cover a wide range of mainstream journal titles; for example, journals such as "Construction and Buildings Materials" contributed 37 articles. According to internal statistics from Scopus (2022), this journal is rated top 10 and 7 of 136 in their "Construction and Building Technology" and "Civil Engineering" categories, respectively. This means that AM-related research is being published in top-rated

construction and civil engineering journals, which is evidence of its expansion and growing acceptance. Analysis of conference paper publications provided additional support regarding this point; 88 unique conference publications contributed 163 sourced papers. Furthermore, conferences such as "IASS 2019" provided 6 papers from a single year, which is significant when considering that ISARC contributed 23 papers over multiple years. It was also explained in Chapter IV that IASS 2020 would have probably provided even more papers, but the COVID-19 pandemic forced its cancellation. Nonetheless, the analysis showed that more recent conferences are producing a greater number of papers than their predecessors, providing evidence that construction industry-focused AM research has increased.

The bibliometric analysis also explored the most prolific journal article authors by primary contribution and a combination of primary and "secondary" contributions. Results of this analysis showed that 46 authors were considered primary contributors to at least two or more journal articles. Publications from these authors, who make up 13.4% of journal authors, accounted for 32.9% of all sourced journal articles. As expected, these authors are arguably the most influential group of researchers in the field, but unique authors (298) still represent a significant portion (67.1%) of the published journal works. Therefore, it was inferred that the research field benefits from a wider perspective of new ideas.

The last portion of the bibliometric analysis determined the top 20 articles by total citations. Unsurprisingly, the majority of the top 20 contained articles from earlier years (i.e., before 2019), as older articles tend to have more citations because of the amount of time they have been available. That said, a more recently published article, "Metal 3DP

in Construction: A Review of Methods, Research, Applications, Opportunities, and Challenges" by Buchanan and Gardner (2019), was present in the 19th spot. This article's inclusion is most likely for reasons explained in Chapter IV; in short, metal 3DP in construction is a relatively limited concept so it is reasonable to assume that articles referencing the technology would have greater numbers of citations. It was also notable that of the top 20 articles there were none with significantly more citations, which is indicative of a well-balanced research field with a growing number of perspectives and innovative ideas.

The knowledge gained during the bibliometric analysis can be leveraged to answer Investigative Question 1, which states, "*What is the current status of published research of AM in the construction industry through the analysis of scientific journals and academic papers?*" From the analysis, it was shown that the construction industry-related AM research field is growing at an exponential rate, starting in 2015. Furthermore, relevant journal articles and conference papers are present throughout a growing range of reputable publications and conferences, respectively. The research is also being driven by many different authors and published articles, allowing for the assimilation of varying perspectives and the introduction of new, innovative ideas.

Conclusions of Scientometric Analysis

In the first part of the scientometric analysis, a word frequency analysis was performed to explore the top 100 most frequently used terms within the abstracts and keywords of the sourced articles. The results of this analysis found that terms such as "concretes", "materials", and "reinforcing" were among the more prevalent. Of these,

“concretes” had the greatest use, with a count of 1553, which is indicative of the research’s focus on the use of 3DPC, which was reviewed during Chapter II. This is supported by the high use of “materials”, which is indicative of the research focus on the material rheology of 3DPC. The relatively high use of “reinforcing”, at 394, is also evidence of the focus on one of 3DPC’s greatest challenges.

The results of this first analysis were echoed in the next two portions of the scientometrics analysis, which included network, density, and time-series mapping of the top 100 and top 40 terms, and the calculation of descriptive statistics like degree of centrality. For example, the density maps were used to determine that terms such as “cementitious materials”, “concretes”, and “reinforcement” were a common focus for the majority of research articles. Additionally, the calculation of the degree of centrality supported the conclusion made using the density maps, wherein terms like “concretes”, “materials”, and “reinforcement” were amongst those with the highest degree of centrality. This means that these terms (nodes) are some of the most highly connected within the research network, which is directly related to their overall importance within the field. Furthermore, the time-series maps were leveraged to explore when terms were most commonly used, thereby providing context on previous and recent research trends. From this analysis, it was found that terms such as “digital fabrication”, “robotics”, and “computer-aided design” were most commonly used before 2018, meaning that their importance to the research field has waned in recent times. Alternatively, “rheological property”, “reinforcement”, and “concrete mixtures” terms showed evidence of their increased use during more recent years. From this, it can be inferred that these topics are some of the more important ones, meaning that focus on them has been recently growing.

The last part of the scientometric analysis, which was a trend analysis of the last 12 years of data, expanded on the results from the time-series maps. With this trend data, terms such as “materials” and “reinforcement” were shown to have high increases in their use frequency, thereby supporting the inference of their importance to the research field. Surprisingly, “architectural” was a term that was found to have a significant decrease in its use, with zero occurrences in the years after 2016. This is representative of a shift in the thinking behind the application of the AM in the construction industry from a strictly architectural tool to possible construction practice. Unsurprisingly, this decrease coincides with the increase in the occurrences of the previously mentioned terms, meaning that researchers started exploring options to make AM products structurally capable once interest for a strictly architectural technology disappeared.

The results of the scientometric analysis can be used to answer Investigative Question 2, which states, “*What key areas of additive manufacturing’s use for construction has the research focused on? Which of these areas share the bulk of the focus? What trends are presented in research topics during recent years?*” Using the visuals and data, it was shown that the bulk of research is focused on materials and reinforcement. Other areas of interest include robotics, strength, and tests. Use of the density maps and degree of centrality calculations confirmed the overwhelming focus on the listed terms, meaning that these areas are some of the most important, requiring innovation and adaptation before AM can become a significant factor in future construction operations. The research trend was also shown using time-series mapping and trend analysis, both of which found that areas like materials and reinforcing are the

most consistently researched during recent years, highlighting once again the importance of these factors.

Additional Conclusions

The third and final investigative question states, "*What advantages and disadvantages of the technology could influence the adoption of additive manufacturing practices in construction applications? Are these translatable to meet the requirements of large-scale construction and/or DoD applications?*" This question requires the integration of knowledge gained throughout the research and the subjective assessment of it to form an opinion regarding the future of AM technology within the construction industry and the DoD. As reviewed during Chapter II, the advantages of AM are significant. From reductions in cost and environmental impacts to increased safety and structural optimization, AM is poised to dramatically change the landscape of the construction industry. Of these advantages, cost and environmental impact reductions are arguably the most appealing to the construction industry. Unfortunately, these are probably the most contentious advantages, with many publications arguing the presence of the benefits or lack thereof. For example, AM was found to be more economical in small, customized batches while pre-cast techniques were more favorable with increased production scales (Weng et al., 2020). Furthermore, the environmental impact of using the higher OPC-concentration 3DPC mixes dramatically impacts the advantages of the technology (Han et al., 2021). This uncertainty is most certainly a significant roadblock to the adoption of AM in the construction industry.

The challenges associated with AM, which are material rheology, reinforcement, and construction standards, are also preventing its widespread adoption. Of these, the development of 3DP construction standards is subjectively the most significant problem for researchers. This is true because one would be hard-pressed to find a construction company that would produce a commercially available 3DP structure without guidelines or universal standards like those published by organizations like ASTM. Without these standards or guidelines, a company would essentially be accepting all legal liability should something happen to that structure (Yang et al., 2018; Zuo et al., 2019). Additionally, with standards in place, researchers could better focus their efforts on material rheology and reinforcement techniques to meet specified requirements. That said, continued progress towards better solutions to these challenges brings AM closer and closer to industry adoption.

As for AMs implementation within DoD practices, some research has already explored the possibility of using AM to produce military-specific components like dragon teeth (i.e., concrete vehicle obstacles), defensive fighting positions, and barracks huts (b-huts) (Kreiger et al., 2020). However, as with many of the commercial studies, these examples are relatively small in scale and produced in highly-controlled research settings. That said, AM’s benefits in speed and durable construction, as referenced by Bayley and Kopac (2018), could provide the DoD with a breakthrough capability when it comes to rapid deployment and bare base beddowns. For example, a deployable printer could produce 3DPC billeting structures similar to the current practice of using relocatable buildings (RLBs) (i.e., shipping containers) but with many advantages. The 3DPC would be much more durable, from both normal use and potential threats, while also

implementing topological optimization to introduce passive effects (e.g., better insulation and sound attenuation characteristics). Unfortunately, much like the commercial industry, the DoD still requires a significant amount of research before AM can be implemented on a practical scale.

In Chapter II, many promising advancements in AM were reviewed, but if the DoD was to implement this technology immediately, the best strategy would be to pursue an extrusion-based system such as contour crafting or concrete printing. This technology would need to be combined with a variety of reinforcement techniques like fiber-reinforcement, post-tensioning, and/or WAAM reinforcement installation. Additionally, and arguably more critically, the DoD should adopt a suitable 3DPC mix design that meets the important four rheological characteristics while also being globally available. This mixture would also require the implementation of construction standards for 3DPC, as the DoD needs to provide suppliers with proper benchmarks for quality assurance and control practices. While this goal may seem extensive, the DoD undoubtedly has the need, capability, resources, and technical expertise to pursue AM construction and accelerate its widespread adoption into the construction industry.

Significance of Research

This research provided an in-depth look at the current status of the construction industry-related AM research. The value of this study is two-fold; first, it provided a comprehensive review of state-of-the-art AM technologies, their applications within the construction industry, and the advantages/challenges of the technology. Second, the study presents insightful information on current trends within the research field and

which areas are of the highest importance. Therefore, this study bridges a gap in the literature, as scientometrics has not yet been applied to this field.

The DoD and Air Force should take note of this study, as it presents the advantages of this disruptive technology. This research also clearly defines the limitations of AM and the areas requiring more research/innovation. The DoD could use these defined limitations and required research areas to focus its significant R&D budget to advance the technology, harness its advantages, and produce better infrastructure for its personnel. AM is also uniquely geared to fill a gap in humanitarian, rapid deployment, and bare base beddown operations, in that it has been shown to produce durable components/structures with minimal labor requirements. This capability could be integrated into current military construction units (e.g., Seabees, RED HORSE) and/or contracted out. While these milestones may still be far from realization, the importance of AM research cannot be understated (this study notwithstanding), and the DoD should continue its development through programs like those at the U.S. Army's Engineer Research and Development Center -Construction Engineering Research Laboratory (Kreiger et al., 2020).

Recommendations for Future Research

In a research field that moves as rapidly as AM, constant research is required to stay informed on the many innovations being made. This research provided a broad look into the field of AM research, but future scientometric studies could be conducted at a more focused level to provide more insightful information about those topics. For example, adjusting the search parameters could yield drastically different source data,

thereby possibly impacting the final results. Additionally, a similar scientometric study could be performed using an alternative database such as WoS.

Continued research focused on the challenges of AM is also required. Focused research into topics such as the implementation of construction standards, differing reinforcement techniques, and improved materials would surely produce innovative results to advance the body of knowledge. Practical case studies could also be performed, either conducted or reviewed by researchers, especially ones focused on the practice of AM constructed infrastructure. This area could also be explored in the DoD, where AM's implementation into construction operations could be examined.

Summary

Research into the use of AM technology within the construction industry has continued to evolve and grow since the first studies in the late 20th century; therefore, periodic reviews of the field are required to assess the current state and determine the feasibility of implementing it into commercial use. Through the use of scientometrics, this research provided that review and assessment regarding the current state of the literature. In this study, quantitative and qualitative methods were applied to a dataset of 522 articles, which was sourced from Scopus, and analysis was conducted with four textual data mining and reference management software packages (NVivo 11.6, VOSviewer 1.6.17, Gephi 0.9.2, and Zotero 5.0.96.3).

Results of this assessment showed that since 2015, construction industry-related AM research has grown at an exponential rate. In addition, the research data is attributed to a wide range of journal publications, conferences, and authors, which provide the field

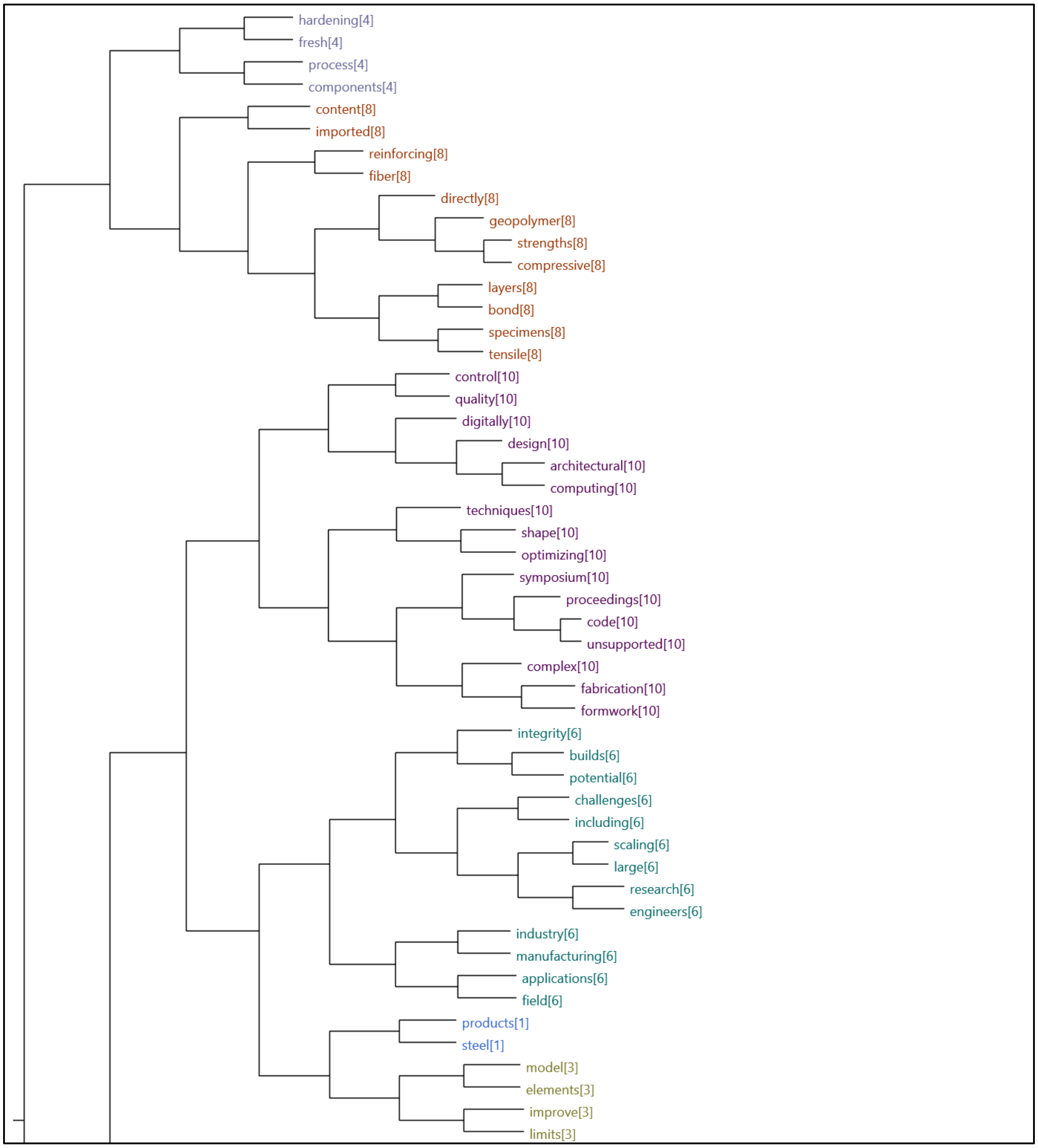
with a variety of perspectives and innovative ideas. In its current state, AM research was determined to be focused on three key areas, which were materials, additives, and reinforcement. These areas coincided with key challenges facing the implementation of AM technology in the construction industry, which were reviewed in Chapter II. Using the knowledge gained during this study, it was also concluded that AM technology has a promising future in the commercial industry and DoD, but much more research is required before its widespread implementation.

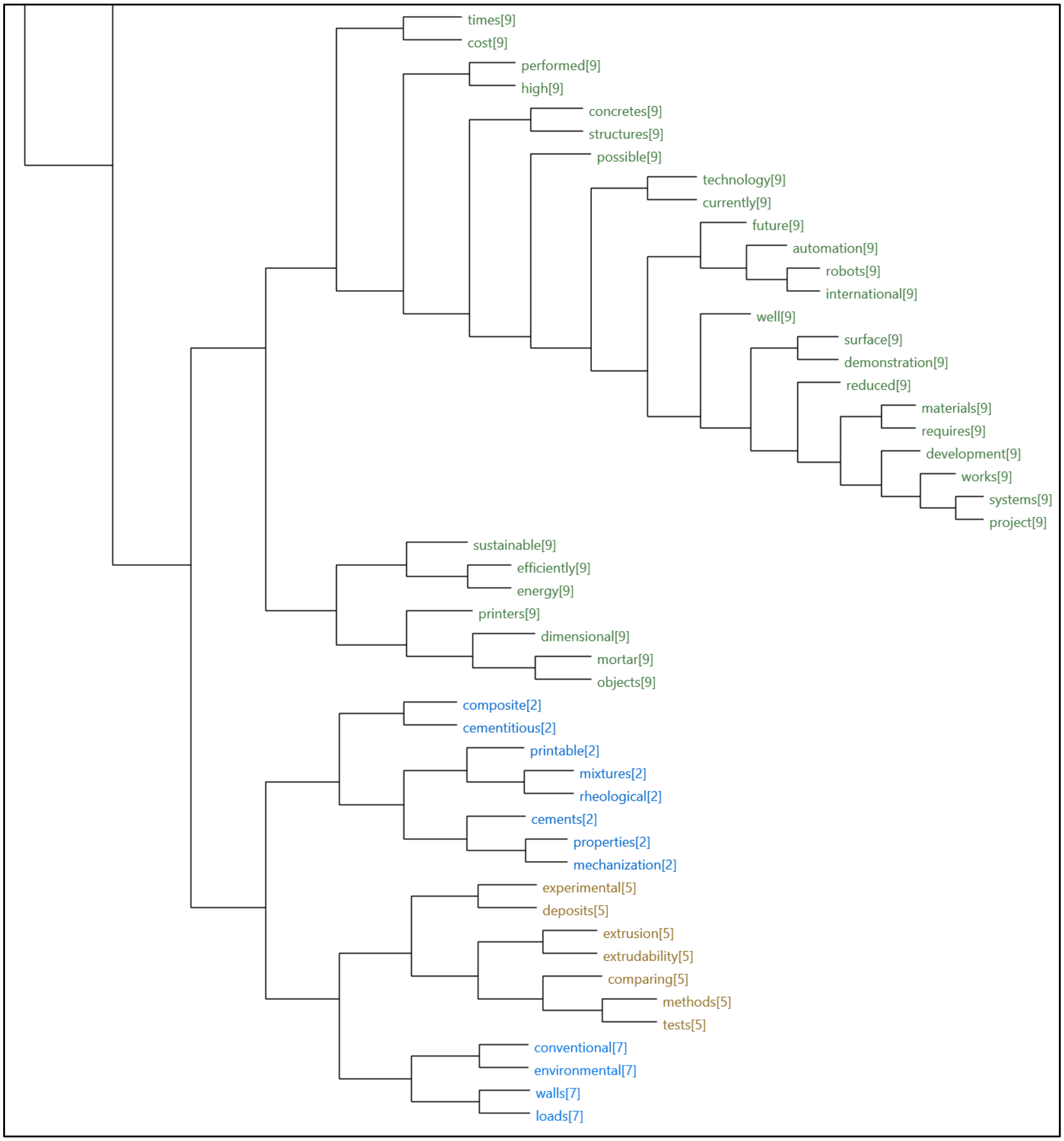
This study was important as it provided a state-of-the-art review of the AM literature while also providing an insightful look at current trends and areas of high importance. This research also paves the way for more in-depth, topic-specific reviews of key areas. It is the hope that this study is used to provide that pathway for future research endeavors into the construction industry-related AM field.

Appendix A. NVivo Stop Words

1990	analyzing	designates	hasn't	indicating	number	relatedly	suggests	very
1991	and	designation	have	inform	of	relates	term	was
1992	any	designer	haven’t	informal	off	relating	termed	wasn’t
1993	approach	did	haven't	informality	on	researched	terms	wasn't
1994	approach’	didn’t	having	informally	once	researcher	than	we
1995	approached	didn't	he	informant	one	researchers	that	we’d
1996	approaches	differ	he’d	informants	ones	researchers’	that’s	we’ll
1997	approaches’	differed	he’ll	informing	only	researches	that's	we’re
1998	approaching	difference	he’s	informs	or	researching	the	we’ve
1999	are	differences	he'd	into	other	reserved	their	we'd
2000	aren’t	different	he'll	investigate	ought	results	theirs	we'll
2001	aren't	differently	her	investigated	our	rights	them	were
2002	article	differing	here	investigates	ours	said	themselves	we're
2003	articles	differs	here’s	investigating	ourselves	same	then	weren’t
2004	as	discuss	here's	investigation	out	say	there	weren't
2005	at	discussed	hers	investigational	over	says	there’s	we've
2006	author	discusses	herself	investigations	own	shall	there's	what
2007	authors	discussing	he's	investigative	paper	shan’t	these	what’s
2008	authors'	discussion	highly	investigator	positive	shan't	they	what's
2009	authors’	discussions	him	investigators	positively	she	they’d	when
2010	based	do	himself	is	present	she’d	they’ll	when’s
2011	be	does	his	isn’t	presentation	she’ll	they’re	when's
2012	because	doesn’t	how	isn't	presentations	she’s	they’ve	where
2013	been	doesn't	how’s	it	presented	she'd	they'd	where’s
2014	before	doing	however	it’s	presenting	she'll	they'll	where's
2015	being	don’t	how's	its	presently	she's	they're	which
2016	below	don't	i	it's	presents	should	they've	while
2017	between	down	i’d	itself	print	shouldn’t	this	who
2018	bibliographical	during	i’ll	i've	printed	shouldn't	those	who’s
2019	both	each	i’m	key	printing	show	three	whom
2020	busy	effect	i’ve	keywords	printings	showed	through	who's
2021	but	effects	i'd	leads	prints	showing	to	whose
2022	by	elsevier	identifiable	let’s	projecting	shows	too	why
a	can	exist	identified	let's	projection	shows'	under	why’s
about	can’t	existed	identifiers	library	projections	significance	understand	why's
above	cannot	existence	identifies	literature	projective	significant	understandable	will
abstract	can't	existent	identify	ltd	proposals	significantly	understandably	with
addition	cited	existing	identifying	make	propose	so	understanding	within
additional	conference	exists	if	makes	proposed	some	understandings	won’t
additionally	conferences	few	i'll	makings	proposes	studied	understands	won't
additions	context	find	i'm	may	proposing	studies	universal	would
additive	construct	finding	impact	me	provide	studies'	universalism	wouldn’t
additively	constructability	findings	impacts	more	provided	study	universality	wouldn't
additives	constructed	finds	importance	most	provider	studying	universally	you
after	constructing	firmly	important	mustn’t	providers	success	universe	you’d
again	construction	first	importantly	mustn't	providers’	successes	until	you’ll
against	constructions	firstly	in	my	provides	successful	up	you’re
all	constructive	firsts	inc	myself	providing	successfully	upon	you’ve
also	constructs	for	increase	need	publication	successfulness	us	you'd
am	could	from	increased	needs	publications	such	use	you'll
among	couldn’t	further	increases	no	reference	suggest	use'	your
an	couldn't	had	increasing	nor	references	suggested	used	you're
analysis	data	hadn’t	increasingly	not	referred	suggesting	useful	yours
analyze	date	hadn't	indicate	note	refers	suggestion	usefully	yourself
analyzed	designate	has	indicated	noted	relate	suggestions	usefulneuses	yourselves
analyzes	designated	hasn’t	indicates	notes	related	suggestive	using	you've

Appendix B. Enlarged Dendrogram





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technology[9]
currently[9]
future[9]
automation[9]
robots[9]
international[9]
well[9]
surface[9]
demonstration[9]
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materials[9]
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development[9]
works[9]
systems[9]
project[9]
sustainable[9]
efficiently[9]
energy[9]
printers[9]
dimensional[9]
mortar[9]
objects[9]
composite[2]
cementitious[2]
printable[2]
mixtures[2]
rheological[2]
cements[2]
properties[2]
mechanization[2]
experimental[5]
deposits[5]
extrusion[5]
extrudability[5]
comparing[5]
methods[5]
tests[5]
conventional[7]
environmental[7]
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loads[7]

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14. ABSTRACT
Review of construction-related AM literature is used to identify the advantages, challenges, and current trends of the research. Using a scientometric analysis of 522 bibliographic records, this research systematically analyzed construction-related AM research to determine the key research areas and trends. Results showed that starting in 2015, the field has been growing at an exponential rate. Recent AM research focused on materials and reinforcement topics, which matched the most notable challenges of AM, which are material rheology, reinforcement, and lacking construction standards. This study provides an insight into AM research and identifies areas requiring more innovation before its commercial acceptance.

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