

**The Implementation and Development of 3D Concrete Printing
for On-Site Applications in Construction**

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Abstract

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Construction innovations are developing in an increasing number of applications around the world. Of the proven innovations, Additive Manufacturing (AM) has been found as a staple process which demonstrates immense potential across manufacturing and industrial applications. Yet, it has not found its place in the construction field. The construction industry has been slow to adopt many emerging innovations since the early tech era. However, it has demonstrated recent adoption tendencies among specific design and management application. For a construction application of AM, 3D Concrete Printing (3DCP) revitalizes a new hope for increased productivity, customization and sustainability options while reducing construction costs, construction time, manpower and potential hazard exposure. At the current stage of development, 3DCP is encountering numerous technical challenges and field considerations for applications on and off construction sites. It is the aim of this thesis to examine integration

factors of this innovative technology into the construction sector while exploring the potential impacts and outcomes of 3DCP as that groundbreaking technology. Based on a review of literature surrounding the 3DCP practice as well as the industry sector, interviews were conducted on partners active in an ongoing research project seeking to develop the next generation of 3D concrete structures. Analysis of the responses aim to provide a basis of understanding for the technology's performance, industry adoption and on-site integration of 3D printers. Thus, this exploratory study seeks to compile the internal and external considerations to provide initial research into the adoptability of a promising technology.

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Chapter 1. Introduction

1.1 Background

The field of construction is changing rapidly. With internal and external pressure to evolve practices to keep up with large backlogs, industry partners are increasingly required to keep up with productivity demands while contorting to sustainability requirements. The industry has been commonly degraded as the slowest and most resistant to innovation adoption. External forces are pushing the industry towards a tipping point where something has to give. The sector is one of the largest in the global economy while averaging 1% labor-productivity growth per year compared to 2.8% for the world economy and 3.6% manufacturing (McKinsey & Company, 2017). The construction process is further burdened by waning labor abundance and increasing workplace injuries and illness. The global housing shortage is seen as a humanitarian crisis with almost half a billion people expected to survive in substandard housing by 2025 (Woetzel et al., 2017). On top of these issues is the global challenge of CO2 emission reduction which the construction industry and buildings are responsible for nearly 39% of global emissions (World Green Building Council, 2017).

The automation of construction processes is not a new idea in the industry. The manufacturing and agriculture sectors have adopted robotic, production line styles of operation with significant gains to show for it. “Conventional construction gives birth to new technologies, which at the beginning phase (where we presently find ourselves) are inferior in performance due to technical, organizational, and economical obstacles as well as to limited integration within an economic environment still dominated by mature and conventional technology,” (Bock, 2015). In the journal *Automation in Construction*, the inclusion of robotics has provided a new horizon for discovery in the quest to raise the technology level of the construction industry. Robotics in construction cannot in the same way be overlaid as manufacturing has been due to project versus product characteristics, complexity, duration, materiality and numerous others (Bock, 2015). Thus, new methods and considerations must be given to robotics used in construction applications. The most prominent being off-site manufacturing of prefabricated building components. This process has been more capable of integrating automated activities due to similarities with manufacturing styles of production. There are also examples of automated tasks on construction sites for particularly hazardous or repetitive work such as automated brick layers,

welding robots and demolition/abatement robotics. Robots in general are becoming more user-friendly, less expensive, multi-functional and adaptable. Automation will become an increasingly important aspect of the industry as advances progress through cost-efficiency and other industry issues become more cumbersome.

One specific practice in particular which has gained a foothold in various sectors is additive manufacturing. The layered deposition of material to form a 3D structure has become a staple method of creation for unique and complex geometries. It can be found in numerous sectors including aerospace, medical, transportation, manufacturing and even the food industry. With each material comes unique challenges with material characteristics and printing parameters. Among the variety of materials possible for printing is concrete via the Contour Crafting method. This method has given way to several other styles of production currently being researched on in countries around the world. Developed by Professor Behrokh Khoshnevis from the University of Southern California in the early 2000's, this system of 3DCP has shown potential for intricate designs and large-scale structures. It opens possibilities for countless applications with numerous benefits across all levels of the production lifecycle. The practice is finding a place in the housing sector by being able to print entire houses in a few days as well as the design realm due to its ability to complete highly complex building elements. It is projected that the 3D construction printing market grow from 3 million USD in 2019, to 1,575 million USD by 2024 (MarketsandMarkets, 2019). Numerous obstacles stand between 3DCP and its deployment on-site. There exist issues with materials and print parameters, rheology and mix designs, geometry



Figure 1.1: "BOD2" Printer (cobod.com)

and scalability, robotics and procedures. However, with knowledgeable entities propelling 3DCP research, it is only a matter of time until this novel innovation breaks through to the construction site.

1.2 Study Overview

The following chapters explore the existing knowledge around 3D concrete printing. It is the intention of this research to develop new knowledge surrounding the current and future applications of this technology. At the heart of this study is an analysis of 3DCP's ability to integrate with the building/design industry, specifically to the construction site. These are summarized in the research questions this study aims to answer.

- What are factors that influence 3DCP integration on construction sites?
- What is being done in 3DCP development to ensure integration occurs?
- Why is the integration of this technology important for the industry?
- How will the integration of 3DCP change construction?

This research is organized in a typical thesis format with six total chapters, four of which provide information on the research at hand. These chapters are as follows.

Chapter 2. Literature Review: The examined literature covers topics surrounding the process of concrete printing as well as its modern competitors among other challenges the technology faces. Building and design issues of the industry are also reviewed as well as the processes in which it may go through in order to become a mainstream practice. This chapter provides an expansive overview of numerous aspects in 3D concrete printing's realms of operation.

Chapter 3. Research Methodology: This chapter explains the process and concerns of how the study was performed. The data was collected in one-on-one interviews of a particular 3DCP project example.

Chapter 4. Data Analysis and Discussion: The results of the data are organized through a thematic analysis of topical areas determined by common literature themes from chapter 2. These areas guide the analysis and discussions chapter. The interview responses are categorized in this manner to align the research with potential blind spots in existing literature.

Chapter 5. Conclusion: The closing chapter highlights key points in existing knowledge, study results, and the result's significance and potential areas of future research.

Chapter 2. Literature Review

Literature from a variety of relevant practices and research areas were examined in this chapter to provide context for 3DCP technology. The review begins with works describing the historical and current state of concrete practices used in the modern construction industry. The intent of this chapter is to examine a wide range of knowledge relevant to 3D concrete printing. This chapter will further cover the current 3DCP research, relevant applications and similar practices. Industry issues the construction industry in the United States and Denmark face due to a variety of contributing factors will be examined in the context that 3DCP might provide relief. These issues include productivity concerns, labor/skills shortages, worker safety issues, global housing shortages and sustainable building methods. The digital concrete production process as well as robotics and automation in construction will be reviewed to provide the setting for the state of the industry as well as similar concrete technologies. The concrete printing literature will then be further reviewed for its technical processes and challenges in development. At the heart of this research is the interaction between 3D concrete printing and the field work on construction sites. The interface between the technology and the field is the primary aim of this research to understand the effects it makes on-site as well as in a controlled environment. In the final sections, 3DCP will be reviewed from a technology performance perspective and its outcomes of adoption for the future. At the end of the review, research questions derived from the literature will be presented which will guide the remainder of the study through a thematic analysis.

2.1 Concrete Construction: Traditional Concrete & CNC Customization

The concrete structures built today are produced primarily using two methods: 1) traditional formwork techniques with formwork built by carpenters and 2) Computer Numerical Control (CNC) milling where builders use machines to cut the formwork. The current norm for non-standard geometric forms is by way of CNC-milling, which allows for an abundance of design options when used in conjunction with traditional formwork. These methods can be attributed with nearly all concrete structure's creation. These methods of casting concrete remain the dominant and most cost-effective practice, which typically involve simple geometries and standardized mix designs. However, with many industry considerations such as productivity, sustainability and several others, investigations into new practices are required to stride forward. It is only a matter of time before new methods replace the old and open up design possibilities

and improved material efficiencies along the way. These methods are described to provide an understanding for how formworks are customized today.

Traditional Concrete

Traditional concrete construction methods can be characterized by formwork techniques utilized up until the use of CNC milling. The common methods of formwork often involve timber, plastic, fiberglass and metal materials to act as sheeting, wales, studs, plates and other component specific requirements. Another distinction in standard forming practices is between conventional and engineered formwork. Conventional formwork typically uses wooden materials, fabricated to the specific application, requires relatively more man-hours for construction, but may be reused if treated carefully. Engineered formwork acts as prefabricated sections of forms, which can be re-used many more times all while increasing efficiency and safety during erection (Forming America, 2016). Where these two long-time methods coincide, is in the structures left standing after the forms are dismantled. Slabs, columns, beams and walls are the most common applications for concrete used in construction, all of which hold fairly little complexity in their standardized applications. Although wet concrete can take the shape of any form it is cast in, its limitations are derived from project performance metrics such as cost, schedule and quality. It is currently more efficient to produce simple structures using proven methods rather than customized components with bends, curves and angles. Many construction projects utilize conventional methods of wood formwork combined with advanced Computer Aided Design (CAD) software to produce complex geometric forms for concrete. However, while concrete is primarily considered a structural material, more expansive uses in architectural designs as well as creative structural applications have given way to another method of concrete forming.

CNC Customization

Some of the most iconic buildings in the world required non-standardized forms. Forms which were crafted specifically for a structure which might not only serve as a structural component but a unique feature which might distinguish it from the monotony of cookie cutter buildings. CNC customization was not a new practice when it entered the construction industry. Used in manufacturing, CNC has a large variety of material options including plastics, metals, foams,

waxes, woods and everything in between. Where CNC milling has found its place in construction was through wooden formwork. It is a less expensive alternative than other materials and can allow for customized cutting of wood sheeting and blocking. CAD programs allow for the design of any possible desired shape and the CNC milling process develops a package of wood materials that, when assembled, will serve as the customized desired form component. These packages can be entire structures or individual components both of which are completed off-site with various CNC machinery (PERI Group). Although this increased design freedom comes at a higher cost, the practice does not stray far from existing construction techniques or building codes. When used with traditional concrete practices, the buildings of today have proven to allow expansive design possibilities and meet all structural requirements. Although the buildings achieve their desired originality, at what cost and is there a better way. The nature of the CNC customization process is prone to labor intensive, high cost, high waste production outcomes. CNC is a subtractive manufacturing process and thus is prone to waste. Discussed in section (2.3.2) are numerous other innovative concrete construction techniques gaining ground, many of which in parallel to 3DCP and its ability to produce unique geometries and features, without additional construction waste.

Where 3DCP and traditional methods of concrete construction diverge is in the formwork. Simply put, printed concrete does not need it, thus greatly reducing the cost of the concrete. Similarly, the preceding forming techniques bound by geometric considerations have encountered their innovative end. The 3D printing process remains consistent whether the desired element is curved or straight. The technology instead operates with different sets of parameters which require careful observation during the placement process which will be reviewed in section (2.3). The strengths and limitations of both traditional concrete and CNC customization provide useful criteria for analysis when considering digital concrete production. As digital concrete is anticipated to one day become the successor of the often-deemed primitive and wasteful practices of the past century, material efficiency, customization and production accuracy are all factors requiring consideration for the future. It is also important to consider existing industries and the successes and failures of their evolution into the modern-day construction era. As an up-and-coming process, digital concrete technology requires a large breadth of analyses, as its application is not only possible in a controlled facility but in situ.

3DCP has an opportunity to advance the field as a whole by tackling the industry issues presented in section (2.2) while opening a new realm of design opportunities and constructability alternatives.

2.2 Current Industry Issues

In this section, prevalent industry issues are reviewed to examine the context in which 3DCP might enter to provide the benefits it promises. The issues discussed in this section which will also be apparent throughout this study include productivity, labor/skills shortage, worker safety & health, housing shortage and sustainability. However, these deep-rooted issues may not be solved merely by the introduction of one innovation, the significance of the entrance onto the scene brings a hope of further developments and a new way of thinking. The following sections will present the problems in which 3DCP has the potential to impact over the coming decades.

2.2.1 Productivity

Perhaps the most prevalent concern in the construction sector today is with the industry’s stagnant productivity levels. In the US, productivity in high production output industries such as manufacturing and agriculture has increased 15-fold since the 1950’s. While the construction industry has increased a negligible amount (McKinsey & Company, 2017). While it is impossible to say precisely which hindrances are affecting productivity across all industries, some report identifies seven areas of improvement projected to increase productivity by 50-60%.

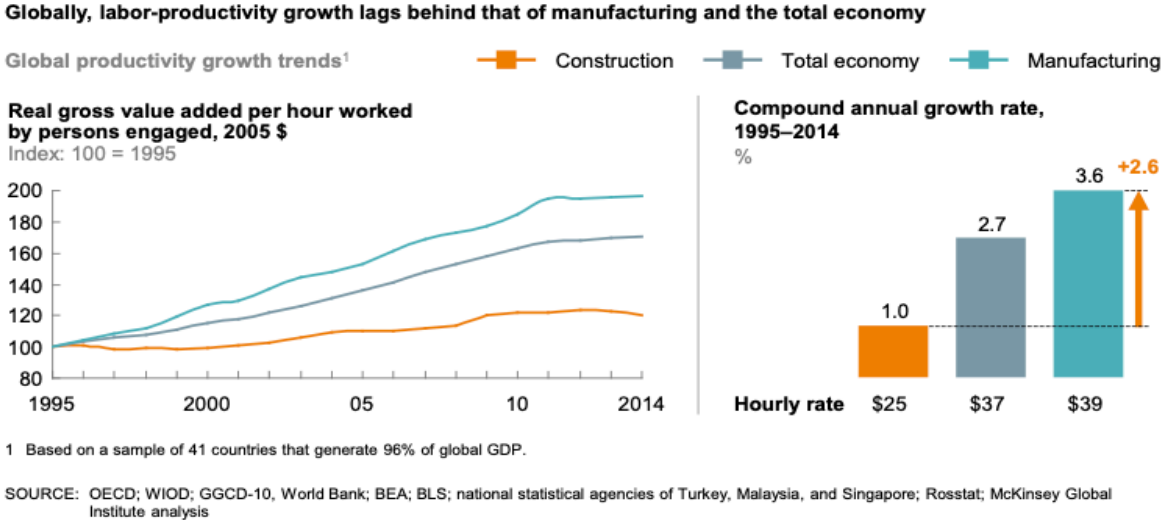


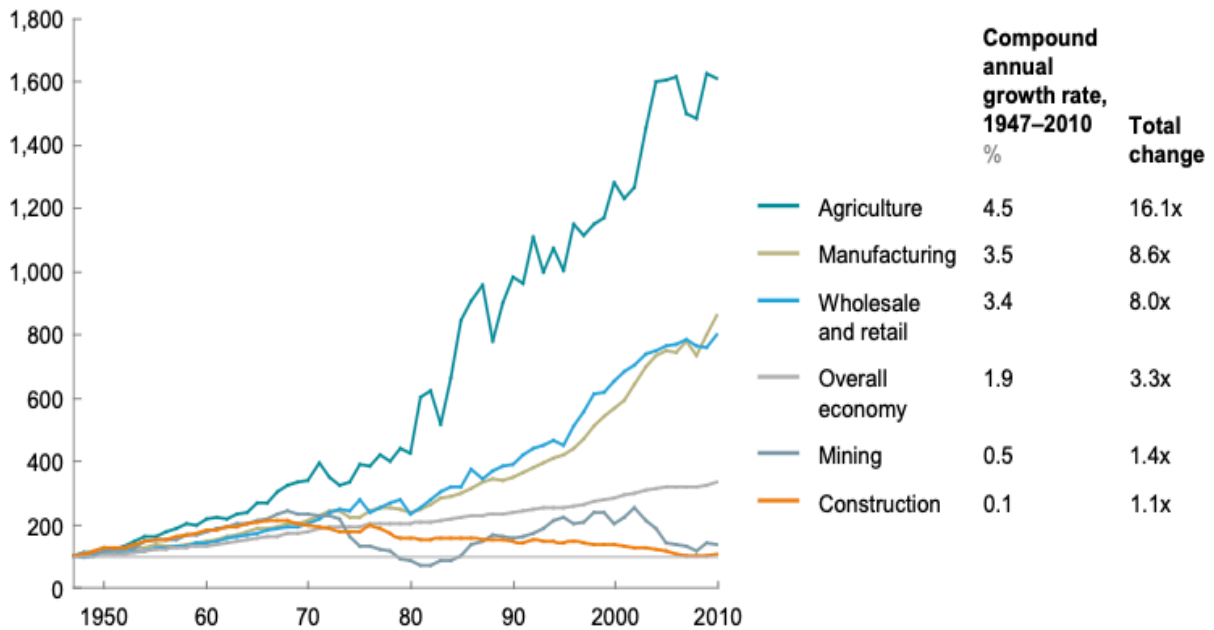
Figure 2.1: Global labor-productivity analysis (McKinsey & Company, 2017)

These areas include: *Reshape regulation, Rewire contracts, Rethink design, Improve procurement and supply chain, Improve on-site execution, Infuse technology and innovation, and Reskill workers* (McKinsey & Company, 2017). Furthermore, a projected 5-10x increase to productivity is possible in specific trades with the adoption of a manufacturing style production system. While it is difficult to directly transfer an assembly line production system to construction sites, prefabrication and modular construction has been gradually increasing in

In the United States, labor productivity in construction has declined since 1968, in contrast to rising productivity in other sectors

Gross value added per hour worked, constant prices

Index: 100 = 1947



Many sectors have transformed and achieved quantum leaps in productivity; construction has changed little, limiting productivity gains

Key advances, 1947–2010

| Agriculture | Manufacturing | Retail | Construction |
|---|--|--|---|
| Leveraged scale through land assembly and automation; deployed advanced bioengineering to increase yields | Implemented entirely new concepts of flow, modularized and standardized designs, and aggressively automated to increase production | Utilized scale advantages and cutting-edge logistics to provide affordable goods to the masses | Limited improvements in technological capabilities, production methods, and scale |

SOURCE: World KLEMS; BLS; BEA; McKinsey Global Institute analysis

Figure 2.2: Gross value added per hours worked (McKinsey & Company, 2017).

prevalence due to a variety of benefits. With the industries project-based versus product-based nature, construction is difficult to completely outsource work off-site. However, integration of technology and innovation has made avenues for opportunity to boost productivity and improve industry aspects in a variety of ways (McKinsey & Company, 2017).

3D concrete printing is an example of the future technology, which may change the face of construction efficiency. Where 3DCP provides the most benefits are by way of *Technical Performance Metrics* described in section (2.5.2). Cost, time, quality, safety and sustainability when optimized for use on construction sites, is expected to provide a faster, safer, reliable and inexpensive output. These potential benefits all contribute to the larger endeavor of improved productivity through reduced incident rates, reduced re-work, reduced material/labor costs, etc. Although the technology is relatively untested, if and when 3DCP breaks into the mainstream industry, the next questions is if anyone will adopt it. Section (2.5) will discuss the challenges and benefits of construction technology integration and whether 3DCP is capable of providing the relief needed to address the productivity concerns of today.

2.2.2 Labor/Skills Shortage

With the global housing shortage ever increasing, the record-breaking number of projects around the world has created a similar shortage in skilled labor. The construction labor market is seeing the baby-boomer generation exit the workforce and with them attitudes and ideals of traditional construction practices. In 2019 there has been an aging workforce and a decreasing number of qualified workers to replace them (Reizen, 2018). A study by the Association of General Contractors (AGC) found the industry is not attracting enough qualified workers and 21% of workers in the construction industry are 55 or older with just 9% who are 24 or younger (Jones, 2018). Older workers are exiting the field faster than younger ones are entering. This discrepancy has contributed to increased labor costs, potentially defective work from insufficient skills, increased rework, elongated schedules and many other downstream effects (Reizen, 2018). Although the precise cause of the shortage is less apparent, the generational incongruence along with the stagnant technological growth has in many ways left the construction market in behind curve. Where construction automation has already begun integration, the labor shortage may not fully be satisfied as advanced technologies are not completely self-sustaining. New technologies

require new skills, skills which take time to learn and trust. The skills required for cutting-edge construction technology have yet to fully be implemented and thus have fewer trained workers to test those skills. Older generations of workers may be more resistant to an automated worksite and even show resentment in fear of job replacement. A study from Beijing found that the perception of automated technology as a threat to their career would more likely result in job crafting behavior and career adjustment. This adjustment comes in the form of individuals seeking new occupation skills and development in an industry different from their current one (Zhang et al., 2019). Unfortunately, with retiring baby-boomers, the change in industry is likely to be retirement with few to replace those vacant positions.

A different study conducted a survey which found cost efficiency and capability of technology for improving productivity to be the most important drivers of adoption (Pheng et al., 2019). Time savings in terms of productivity seems to have a great impact on acceptability of integration. Streamlining processes was the primary goal of prefabrication systems by taking secularized tasks and completing them all in one place, at one time. The end outcome being reduced time. Where there is a shortage of labor and skills, construction automation and 3DCP has the potential to fill that role. 3D concrete printing would require a fewer operators where a cast in place wall would require an entire crew. Similar to other simplified tasks, which might reduce the need for extra labor, 3DCP has the potential to provide relief across several sectors due to the technologies design freedom and advancing reliability of printing outputs. There is concern among workers of the loss of jobs by robots. Worker resentment towards the loss of a job due to a mechanical replacement may be the price of a safer workplace. Findings by (Butt, 2019) saw that 58% of workers are confident AI would not do a better job than them and 55% agree they would rather lose their job to a human than a robot. The labor shortage is just one of several current industry issues that might be relieved by an automated concrete printer as well as the automation of mono-task or unsafe work. Construction automation is discussed further in section (2.3.3).

2.2.3 Worker Safety & Health

The construction industry has been notorious for risky work and injury-prone situations. As the industry remains one of the leaders in fatalities and recordable injuries, improvements must be made. The past decade has shown promise with the introduction of Building Information Modeling (BIM), communication and location software as well as wearable safety technology. However, worker safety and health has yet to see rates fall despite improved construction methods and injuries and illnesses have remained at constant levels (Jones, 2018). For the global industry to upkeep safety regulations with site constant advancements, it creates pressure on project partners and workers to adhere to the rules while delivering a profitable project. For safety measures currently in place, new PPE and safety management software are creating a safer worksite, it remains a critical point of concern for everyone involved in the project delivery lifecycle. As workplace injuries have a significant impact on lost time, productivity suffers greatly when safety is jeopardized. Injuries slow or stop work completely and tend to drain team moral.

There is heavy emphasis in the construction field on worker safety and health. Often deemed to be a part of one of the four keys to a successful construction project being cost, schedule, quality and safety. However, worker safety often takes a backseat to more immediate, managerial concerns and, recently, to innovation. Although 3D concrete printing may not directly make the project safer in the same way designated safety technology will, it has the potential to optimize time-spent on-site. Reduced labor means less hazard exposure, less exposure means fewer potential injuries, less injuries means less likelihood of fatalities. In a 3DCP prefabrication environment, controlled production facilities similar to those of a manufacturing style workspace, unforeseen conditions are severely limited. Studies have shown that off-site prefabrication can change worker perceptions and greatly reduce exposure of hazardous work commonly found on construction sites. In an on-site application, printing areas would be intensively monitored to separate the work areas for the benefit of workers in the vicinity, the printed element and the overall site logistics. Specific on-site interactions of the technology are a primary topic of concern for this research as complete site investigations of printing technology has yet to become available.

2.2.4 Housing Shortage

Of the current industry issues, the housing shortage can be classified as a global humanitarian issue in addition to an industry specific one. The shortage of affordable housing can be attributed to numerous factors such as supply and demand imbalances, rapid urbanization, population growth, finite land resources, legislative regulations, construction industries lagging acclimatization and numerous regional influences. It is estimated 440 million households will be subject to substandard housing by 2025 with current trends continuing (Woetzel et al., 2017). Due to the vast global scale of the housing shortage, attributing only the listed causes to such widespread issues fail to capture the full impacts.



Figure 2.3: ICON printer for housing applications (3dprintingmedia.network/icon-vulcan-ii-3d-printer-construction).

Where affordable housing can be projected for success is by means of prefabricated methods, standardized, predictable units. This is where 3D concrete can have a profound impact. With printers soon to be reliably capable to produce entire structures in one print, it is the hope that affordable housing will be the first type of structure produced on a viable scale. The printer has the ability to quickly and cost-efficiently produce structures optimal for small-scale housing in countries of need (Bos et al., 2016). While print capabilities are expected to grow and scales to increase, so too will the size of the structure and the efficiency of its value added. Although construction related concerns pertaining to housing are only a piece when unlocking the

affordable housing issue, alternative methods of constructability should be explored to tackle this ever-growing problem.

2.2.5 Sustainability

Similar to the housing shortage, environmental awareness and sustainability has also been seen as a global issue and plays a large role in the construction world. “Buildings and construction together account for 36% of global final energy use and 39% of energy-related carbon dioxide (CO₂) emissions when upstream power generation is included,” (World Green Building Council, 2017). With the construction industry standing as such a prominent contributor to the global challenge, it has also become the proving grounds for new technology and methods, which might address the issue. New technologies entering the field have had the ever-evolving benchmark requiring sustainable considerations. Energy savings, resource recycling and reduced CO₂ emissions have become performance metrics with increasing influence on adoptability (Pheng et al., 2019). With concrete’s massive global consumption, comes the cost of serious environmental impact. Building construction and the manufacturing of materials such as cement, steel and glass utilize ~6% of global final energy use (World Green Building Council, 2017). Creating a sustainable material life cycle for concrete waste and raw materials is a point of research in order to break the positive feedback loop of consumption. Since materials used in concrete can be found in nearly all parts of the world, local resourcing is another approach the industry has utilized in reducing costs and emissions. In addition, single-use wooden formwork constitutes the majority of labor and non-value-adding costs to the concrete placement. Custom forms are used and disposed of as construction waste, also another energy sink in the emissions lifecycle. Although these environmental challenges may be addressed in a variety of approaches, 3D concrete printing can arguably be a first step in controlling wasteful practices in concrete construction. While the role played is small in the complex system, by including sustainable considerations early in the technology’s development, future developments will start down the path of more mindful methods.

In the previous sections, the potential for improved productivity, reduced labor requirements and improved worker safety have demonstrated the great appeal of 3D concrete printing on a project level. Early development of the 3D printers suggests there will be reduced operating costs, labor

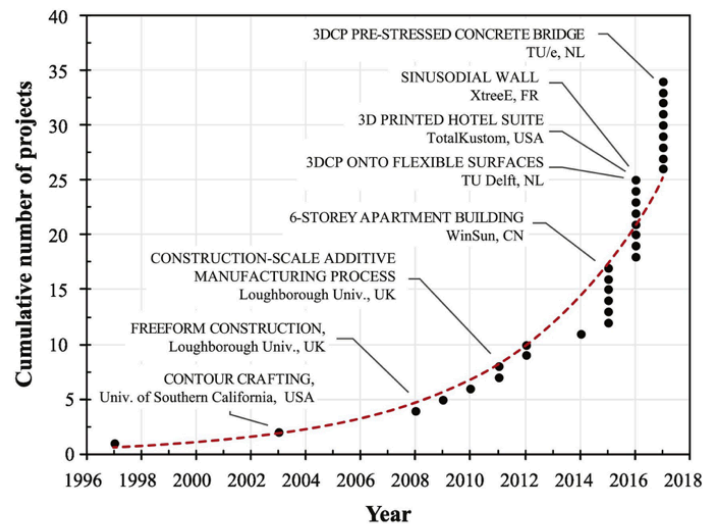
cost, production time, but also material costs and energy usage, further equating to reduced energy, material usage and CO2 emission (Ghaffar et al., 2018). 3D printing is an innovative solution to managing one of the most widely used and most wasteful building material around the world. A direct approach 3DCP has to reducing waste is by way of the lack of formwork and optimized material consumption. There are numerous approaches to sustainable designs and construction which 3DCP aims to address. It is argued the best approach for this solution to be successful is for multi-level, multi-disciplinary collaboration from all backgrounds and specialization in the industry (Ghaffar et al., 2018).

2.3 3D Concrete Printing & Concrete Innovations

2.3.1 3DCP Overview

Additive manufacturing, or the layered deposition and buildup of layers to create structure originally began in the 1980's. The process of subtractive manufacturing has been used for generations before then, which gave way to the modern adaptation of AM for many different industries. A vast range of materials can be 3D printed including plastics, nylon, epoxy resins, metals, organics, concretes and numerous others.

Concrete printing being one of the more recent applications has properties that limit its use in many ways when compared to the original plastic printed materials. For the same reasons that make concrete the most commonly used building material in the world, also makes it one of the most challenging to apply in the practice of 3D printing. The first noteworthy 3D concrete printing example began in the early-2000s with Dr. Behrokh Khoshnevis who developed the Contour Crafting system of printing. This method involves additive manufacturing through layered extrusion aided by a computer model to create precise geometries and designs for full-sized buildings and components. He is considered by many to be the creator of the first 3DCP



Evolution of the number of 3DCP projects and application up to late-2017. (Source: Buswell et al., 2018)

Figure 2.4: Evolution of 3DCP (Buswell et al., 2018).

process, which was later used by other companies and countries as stepping-stones for further advancements. His work provided the basis for many of today's methods for printing full sized structures and elements (Nadarajah, 2018).

2.3.1.1 Robotic Arm System

There are two types of 3D construction printers that have been proven effective in current practice. One of which being the robotic arm printer. Many versions of this style of printer function by printing layers in a radial area nearly 360 degrees around it. Generally, the printer is highly mobile, transportable and can typically print in 6 axes. The robot arm printer is usually used to print smaller elements requiring high levels of detail instead of entire structures but variations in size can allow for larger structures. Their mobility allows for products to be printed on-site for reduced risk of damage during transportation/assembly or off-site allowing for greater control of print conditions (COBOD International A/S). The robotic arm printer has found many successes in the realm of prefab component creation for assembly where the gantry system might find difficulties in precision and mobility. Many 3DCP companies competing in the market today including CyBe, XtreeE, Baunit and others including research institutions, have adopted this printing approach (Wolfs, 2015).

2.3.1.2 Gantry Crane System

The gantry crane system operates by printing layers confined within the area of the crane. This system typically has a longer set-up/calibration time but is more cost efficient for larger mobilizations, more stable and more capable of printing larger structures than the robotic arm system. They do not always require continuous printing for entire



Figure 2.5: BOD time-lapse clip by COBOD (cobod.com/videos).

structures and can be used for smaller elements as well as entire structures. The gantry system is more limited in mobility for on/off-site use but both can be accommodated depending on project requirements. It also has the ability to print a wider range of mixes due to the nature of the pumping system, which will contribute to the variety of printable elements. The gantry system has proven to be more versatile in printable products and is heavily researched on for the potential subsiding of the global housing shortage. Other 3DCP companies sectioning market in the larger scale gantry printers include COBOD, Icon, Winsun and various research institutions (Wolfs, 2015, Wu et al., 2016).

2.3.1.3 Printing Process

Model

The printing process begins at the data preparation phase in which the model is created in a Computer Aided Design (CAD) format which is then sectioned into layers to guide the printer for extrusion. In this phase, placement parameters are considered in conjunction with the mix design to account for set rate, temperature, shrinkage, static and dynamic stresses, extrusion rate, nozzle geometry and travel speed. Virtual models and early CAD designs are where much of the behind-the-scenes development currently stands. Models to test print parameters including fluid and solid-state characteristics are tested against physical prints to validate virtual models. As print parameters change, models are updated and a positive feedback loop of progress ensues. However, due to the extraordinary promises of 3DCP, technical considerations such as these are often overlooked, and the readiness level of the processes are exaggerated. From studies conducted at TU/Eindhoven in 2018, successful 3D printed structures are showcased in the bright light of potential triumphs. These structures, however, undergo extensive trial-and-error processes and structural integrity testing to failure of individualized structures resulting in variable outcomes (Salet et al., 2018).

Mix

The mix design is determined simultaneously with the model to ensure geometries and structural requirements will hold up during the printing process. With the absence of traditional reinforcing, great consideration must be given to mix components and admixtures to ensure the element will survive not only the print duration but the extent of its useful life. The mix can be

fed into the printer via batch mixing or continuous mixing. Batch mixing allows for the composition to be constant while printing by adding admixtures for fresh-state property adjustment. Continuous mixing allows for the composition to be adjustable with admixtures available for implementation for fresh and hardened state property adjustment (Leal da Silva, 2017). Depending on the setting speed and mix consistency, consideration of hardening concrete must be given in order to avoid blockages and continuity of layer extrusion. Accelerator is a chemical admixture, which can rapidly reduce curing time for the concrete (Nadarajah, 2018). However, introducing the admixture at the precise time is crucial for the mix to pass through the hose without clogging, while setting quickly enough for the layers to withstand the accumulating of deposition. Many other additives can be included to adjust properties optimal for placement conditions including set retarder and acceleration, plasticizers, stabilizers and many others (Bos et al., 2016, Buswell et al, 2018, Nadarajah, 2018).

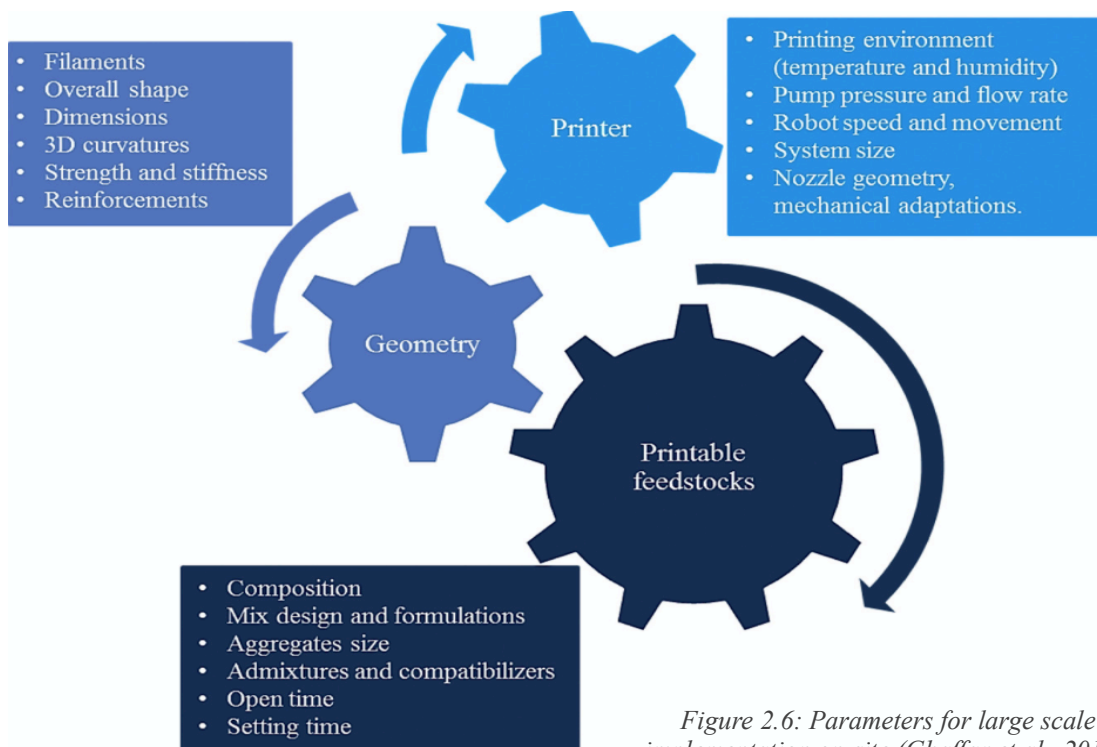


Figure 2.6: Parameters for large scale implementation on-site (Ghaffar et al., 2018).

Print

The printing process is completed with a nozzle attached to the printing arm (Gantry or Robotic), which continuously extrudes the layers. The nozzle properties allow for variable layer thicknesses, geometries and other unique characteristics. Nozzle opening, print speed and pump

frequency are highly dependent on each other as well as the concrete mix design. From the culmination of these parameters, extrudability and buildability are two of the most important aspects of the processes' success (Bos et al., 2016, Nadarajah, 2018). Extrudability is the concrete's ability to extrude as layers from the printer is one of the essential factors for 3DCP success. As standard concrete is able to flow with low viscosity to fill formwork, printed concrete must flow from a nozzle in a similar manner but without deformation. Standard concrete mixes can range in slump values from 1-5 inches depending on the application. Printed concrete requires little to no slump for the process to be successful yet still demands a level of flowability through the pump. At specific locations of the printed element, the nozzle may require a change in speed or head orientation such as corners or curves. Exact deposition of concrete is essential for the element's structural integrity when withstanding the accumulation of layers in its plastic as well as hardened state. Inconsistencies may result in structural failure or poor surface finishes (Bos et al., 2016, Nadarajah, 2018, Wu et al., 2016). As extrudability defines the process prior to material placement, buildability defines the process after deposition. Both extrudability and buildability are the two most important properties for successful 3DCP. This property allows for the accumulation of layers to create the desired structure. Research at the Technical University of Eindhoven determines no slump with chemical admixtures is the ideal mix design to allow for the layers to form and harden prior to the next. However, self-compaction, which is also a critical facet of the mix, contradicts the goal of low-slump mixes (Bos et al., 2016). Various alterations to mix designs can be used to increase buildability of the layers including chemical admixtures, variable temperature, less gypsum cement, aggregate sizes and water/cement ratio. Chemical admixtures are the possible way to increase buildability while allowing for enough open time for the concrete layers to bond between each other (Nadarajah, 2018).

2.3.2 Other Concrete Innovations

The aspect of 3D printing and similar technologies which commands much attention is the ability to free-form incredibly unique structures. It is however not the only

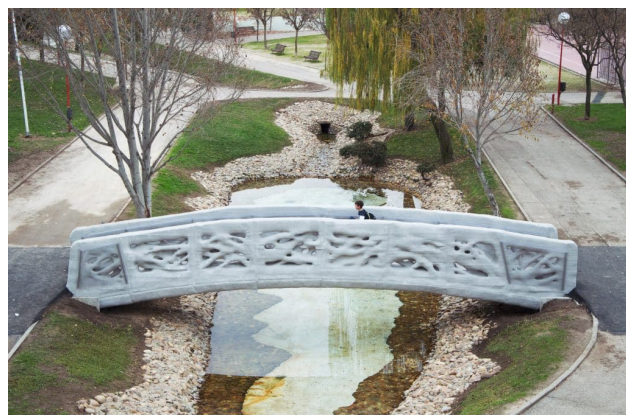


Figure 2.7: Binder Jetting bridge in Spain (iaac.net/project/3d-printed-bridge).

technology to explore the idea of formwork removal. Other advancements move towards technologies such as the Mesh Mould by ETH Zurich dfab system, which utilizes a robot to create a custom wire structure, which acts as not only the structural backbone but the formwork of the concrete. Smart Dynamic Casting also developed by ETH Zurich acts as a slip form and is able to move to a defined shape as the concrete is placed and set vertically. Binder jetting by D-Shape is another technology proven effective by creating the first pedestrian bridge in Spain. This process deposits binder in a bed to harden granular material to create 3D objects (Wolfs, 2015). These three technologies have improved greater design freedom and have the added benefit of reducing material and formwork waste at greater product output. This in turn reduces time spent on non-value adding activities in the workflow. Another practice, Spatial Wire Cutting by ETH Zurich dfab, aims to increase formwork design capabilities without straying too far from proven methods of subtractive manufacturing by using a hot wire to cut unique designs

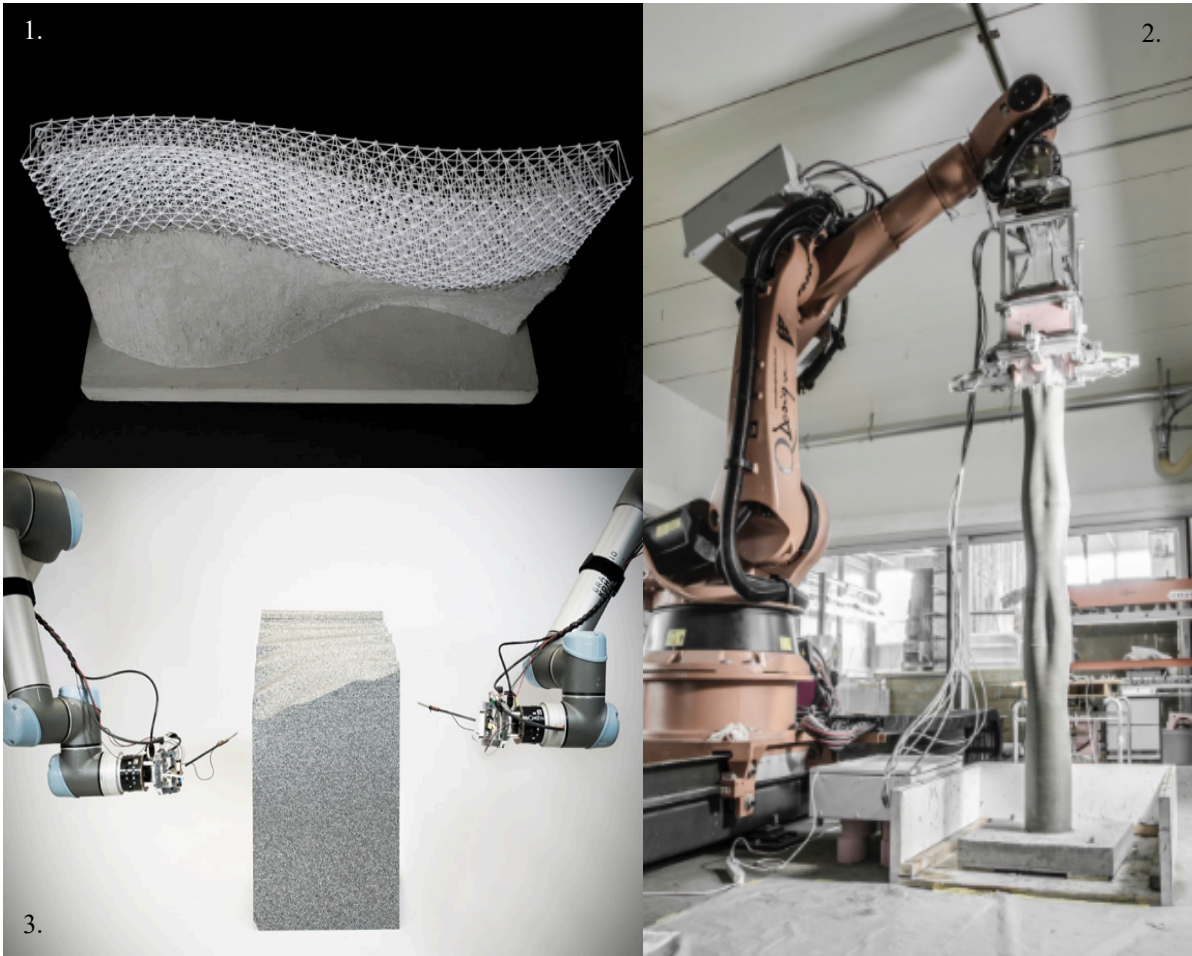


Figure 2.8: Concrete innovations. 1. Mesh Mould, 2. Smart Dynamic Casting and 3. Spatial Wire Cutting by ETH Zurich (gramaziokohler.arch.ethz.ch).

into foam. Although these technologies are advancing towards similar goals, their methods are very different, producing unique challenges and benefits for each process.

Table 2.1: Summary of major digital concrete technologies to date (Wangler et al., 2016).

| Technology | Mould Production | | | Layered Extrusion | Binder Jetting | Slipforming |
|--------------------------|----------------------|------------------------|------------------------|---|--------------------------|-----------------------|
| | CNC Milling | Binder Jetting | Steel Welding | | | |
| Examples | numerous | ETH Zurich dbt | Mesh Mould Metal | Contour Crafting Freeform Construction | D-Shape | Smart Dynamic Casting |
| Advantages | High resolution | | Reinforcement | Shape freedom | High resolution | Reinforcement |
| | High surface quality | | On site potential | On site potential | Cantilevering | Surface quality |
| Limitations & Challenges | | Stay-in-place | | | | Smooth interfaces |
| | Single use | Unbound powder removal | Concrete placement | Reinforcement | Reinforcement | Limited shape freedom |
| | Reinforcement | | | Cold joints | Unbound powder removal | Prefab only |
| | | Formwork pressure | | Formwork pressure | Unbound powder recycling | |
| | | | Layered surface finish | | | |

2.3.3 Robotics & Automation

Construction robotics and the automation of processes are essential for the success of 3DCP. Although much emphasis is placed on the concrete mixing and printing process, the mechanisms of placement are equally as important. Automation in construction has entered the field through the replacement of human labor in repetitive and dangerous tasks. It is argued that many of the existing issues with productivity, labor shortages and other previously mentioned industry challenges could be addressed with the successful integration of construction automation in various points along a project timeline. However, there exists two prevalent issues with construction automation on-site: 1) Integration of existing methods with the new automated ones and 2) The replacement of human element. The first issue is where the partner industry of manufacturing has successfully created output through the product-based production. Construction is limited to the bounds of project-based outcomes, which alter the parameters of production to low turnovers and large scales. The successful implementation of robotics in industry has been in stationary, repetitive tasks involving controlled working conditions and predictable output, primarily in the form of prefabrication. Construction projects involve neither trait and further involve many other unforeseen factors, changing environments, which can negatively affect project quality, productivity, worker safety and schedule. The construction prefabrication industry has been able to integrate automated processes with a manufacturing style

of off-site construction. The next logical step to on-site implementation can be robotic on-site factories with the deployment of Single-Task Construction Robots (STCR's). These factories provide the benefits of both manufacturing environments and on-site logistical ease (Bock, 2015). This is where 3DCP may find its place in the field. The second issue with on-site robotic deployment is in replacement of human labor. With a growing presence of automation on and off-site, the workforce might feel threatened by the shift in work practices. As discussed in section (2.2.2), the mistrust of robots is certainly an issue for successful field implementation by feeling resentment towards the loss of a job to AI (Butt, 2019). While exceptions exist where new technologies have proven their worth to their human coworkers, 3DCP robots have yet to demonstrate ample capabilities in an off-site environment. With the state of the industry growing more dire by the day, it is the hope of many industry stakeholders that construction robotics not only demonstrate greater adaptability to traditional methods but potential to the workforce it will be working alongside.



Figure 2.9: Robotic Arm printer at the Danish Technological Institute (DTI) (Photo by author).

2.4 3D Concrete Printing Challenges to Development

In the field of 3DCP research, there are severe technical challenges opposing the emergence of 3DCP technology's mainstream industry integration. Existing literature on the technology focuses on the capabilities and limitations from a technical perspective. Experiments conducted by the world's leading research institutions and printing companies are focusing efforts on aspects of construction printing essential to structural integrity and overall element quality. While these questions are crucial to success, it is also important to consider the application of the element in production. The research must find its place in the industrial world and without early consideration of the interactions; the advancement is doomed to failure. The following challenges impede the progress of 3D printing and are some of the most commonly assessed issues written in current literature. Later in the section (2.5), these challenges will be examined against the greater question of field implementation and industry adoption.

2.4.1 Early-Age & Mix Design Properties

A commonly overlooked area of concern in the technology's development is apparent the moment the mix leaves the nozzle. Much emphasis is placed on the final, hardened element and bonding strength between layers or the allure of its aesthetics. As layers of the mix stack to create shape, risk of strength based and print based failures arise. These failures are caused by

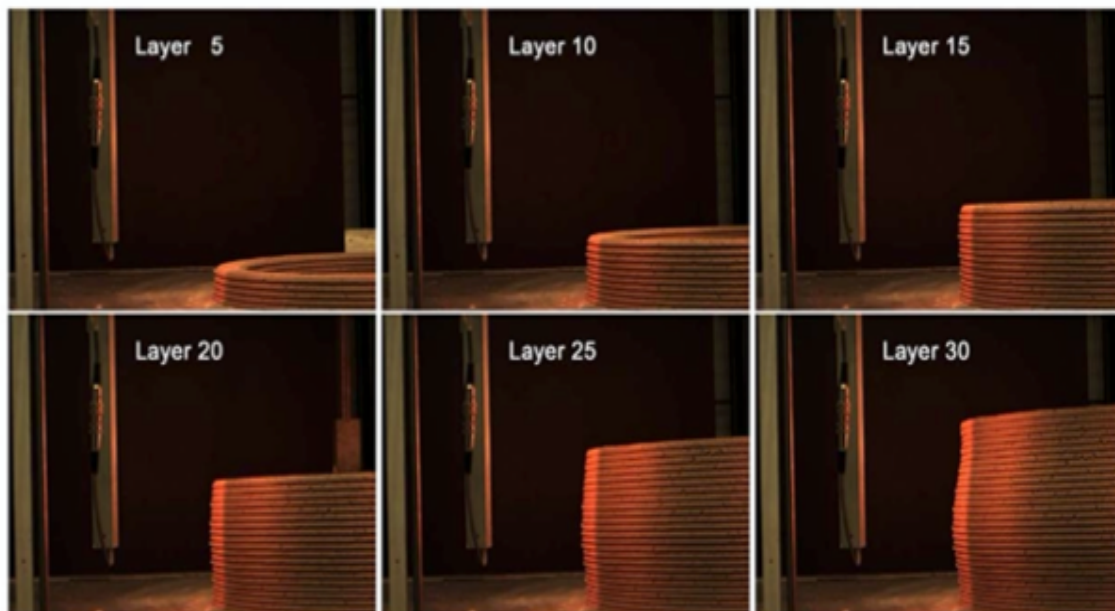


Figure 2.10: Deformation of a cylinder during a print (Wolfs et al., 2018).

the insufficient stiffening of material prior to the next layer and the unpredictability of fresh concrete build-up mechanics during printing. Without the presence of a form to contain the layers, the structure's mix increasingly relies on the cohesion between layers as they print (Wolfs et al., 2018). With many print parameters requiring constant attention in the adolescence of the crafts development, there is high variability in the printed products' outcomes. Many early-age parameters define the final outcome which the technology is so highly publicized. Interfacial strength relies on print parameters such as print and set time, temperature, mix design, mix internal pressure, w/c ratio and others (Wolfs et al., 2018). The effect of concrete mix rheology has yet to be fully analyzed on the extent of the relationships between ingredients and printing outcomes. Research at the Technical University of Eindhoven assumes a strong interdependency between concrete materials, printing process, design and final product, which has yet to be fully understood (Bos et al., 2016). Additionally, due to the high level of virtual modeling dependency, early age printing mechanics prove the most vital to the resilience of the products lifecycle but also the most difficult to predict without the presence of abundant numerical modeling data controlling these tests (Bos et al., 2016). In conjunction with the lack of experimental data on the interconnectedness of these print parameters, these variables play a role in all of the subsequent challenges explained in the following sections.

2.4.2 Reinforcement Strategies

In addition to the challenges confronting rheology and mix design, printed element reinforcement strategies have only further limited the growth of technological possibilities. Although numerous alternatives are being explored for use in experimental development, few strategies can match the strength and durability of traditional steel reinforcing systems. A few placement processes have created some room for creative possibilities with the integration of traditional methods with that of the innovative ideology of 3DCP, such as the printing of concrete to serve as permanent formwork with rebar inside to be filled post-set. However, this technique remains constrained by the singular dimensions of rebar and thus contradicts one of the most important freedoms 3D printing stands for. The unlimited geometric possibilities of the printer are limited to the two-dimensional geometry of a straight steel bar. The rheology around the rebar during placement is another point of research due to the possibility of voids. Other reinforcing techniques which might completely reshape the craft include the Mesh Mould system

with its custom wire printed form and reinforcing system (Wangler et al., 2016). The possibility of fiber reinforced concrete (FRC) is being researched to provide improved structural capabilities while maintaining the freedom of 3-dimensions of mobility. However, the inclusion in the mix could lead to clogging, segregation and non-uniformity (Bos et al., 2016). Generally, reinforcement strategies can be seen widely varied and dependent on the nature of the printed element's size and shape. This results a greater question of replicability and reliability of the reproduced structure, thus further demanding greater research into the developing processes.

2.4.3 Structural Integrity

An area of great concern for 3DCP development is that of the structural integrity of hardened state concrete. If and when the practice reaches sufficiently reliable results during the print phase, the next question to be asked is whether or not the element can survive the rest of its useful life. Regulatory requirements have yet to incorporate printed concrete into the standards for normal use. Eurocode standards cover a range of materials and situations the 3DCP falls into such as codes that apply to batch mixing but not continuous, prefabricated walls but not cast in place, and concrete handling excluding 3D printing. However, without extensive research in these areas, the field will fall into a regulatory grey area with lengthier adaptation times. Additionally, aggregates used in the mixes tend to be small, thus limiting the maximum compressive strength of the element. It is technically incorrect to pronounce the practice as “printed concrete” as the mix more closely resembles that of mortar. Numerous methods of reinforcement are under research in order to elevate compressive and tensile capabilities to



Figure 2.11: Printed beam with embedded reinforcement in 4-point bending (Salet et al., 2018).

acceptable levels. However, the nascence of 3DCP creates a predicament into what level of structural safety is required. This primarily poses a challenge in the application of large scaled structures with load bearing members while instances with non-structural applications may not be under as significant of scrutiny. The topic in question strikes at the heart of 3DCP in that with the immense design freedom that comes with printed concrete, how will it be regulated despite the variations for replicability. Both fresh and hardened state improvements are being explored, but with the experimental results of traditional reinforcement, FRC and in-process cable embedment, predictable structural outcomes will continue to be exploratory in nature (Salet et al., 2018).

2.4.4 Geometries

Great emphasis has been placed on 3DCP capabilities of building in the 3-dimensions of space, expanding the possibilities of concrete shapes and design. Printing concrete bypasses the need for traditional and custom formwork with its mobility and rigidity. While the prospect of endless design opportunity catches much of the spotlight, 3DCP at its core is rather limited in current geometries. A combination of a strong mix and simplistic design will permit the printing of a successful, moderately aesthetic finished exterior. However, geometric challenges in conjunction with each other not only affect the visual finish of the element but the structural integrity. Circular filaments have greater printing geometry flexibility but may lack buildability characteristics due to air cavities. Nozzle height above the deposition also influence the shape and properties of that layer (Bos et al., 2016). Rectangular or square filaments allow for better flowability, solid sections and thus better buildability. Cornering presents the issue of uneven deposition for interior and exterior edges. This leads to non-plumb corners and differing radial curvatures as the structure grows. Offset stacking of layers creates a cantilever effect in order to break into another axes of design space. This practice is quite limited in possibilities as the point of gravity in the layer create uneven distribution of the compressive stress and thus creating uneven, less predictable deformations (Bos et al., 2016). These geometrical considerations currently act as guiding principles for what is and is not possible in 3DCP design. Although the technology still enables great dimensional freedom, there is still a long way to go to claim truly limitless possibilities.

2.4.5 Scalability

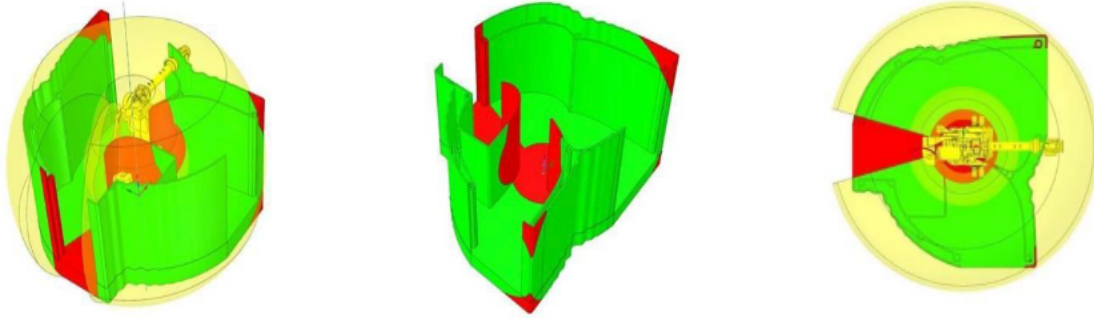


Figure 2.12: Reachable/Printable area of the COBOD printer (COBOD International A/S).

The two printing systems (Gantry & Robotic Arm) play a significant role in the scalability of printed structures. While robotic arm printers are perceived to hold greater precision due to their increased axial freedom, at the cost of print size, they are not completely unable to scale up. Similarly, the gantry printers are predominantly associated with large-medium scale prints due to the greater print area beneath the gantry system. Although both can be scaled up or down to accommodate, the improved precision and design freedoms tend to associate with smaller prints of single elements of lesser complexity. Large-scale prints are made attractive by the possibility of replicable housing structures and even entire buildings. In 2014, WinSun, a Chinese 3D construction printing company produced the world's first villa and a five-story apartment building. Although printed off-site and assembled using a similar process to that of traditional precast concrete structures, many of WinSun's projects demonstrate the scalable potential for 3DCP technology in a commercial construction setting (Nadarajah, 2018). On-site printing proves a much greater challenge due to varying site conditions, unpredictable print parameters and many logistical challenges that confront standard everyday construction activities. Companies like Apis Cor and COBOD, institutions such as TU Eindhoven and MIT have directed efforts into singular housing production, which has the potential to assist in the global housing shortage. While the issue with scalability lies predominantly in the printer size, the culmination of aforementioned challenges plays a role in the eventual success in large-scale implementation.

2.5 Implementation & Effectiveness

At this stage in digital concrete's development, completed projects have been merely to showcase the capabilities of the technology. Outcomes have not been profitable and are nowhere near competitive enough to match traditional methods of construction. Despite clear interest from all parties involved in the building process, it has yet to reach the tipping point where 3DCP companies can provide a profitable product while meeting the societal, economic and environmental standards demanded by the industry. This section reviews the current and long-term adoption concerns of technology on construction sites, as well as the organization as a whole. 3DCP follows the lifecycle of countless technological innovations on the path to field deployment. While technical aspects prove to be a considerable aspect to its progress, end-user external environments for integration will take on a larger role as advancements continue through the next decade.

2.5.1 Technology Adoption

The construction industry has for many years developed a reputation for slow technology adaptation. Although proven by numerous studies that increased assimilation of game-changing technology into business activities provides numerous benefits to productivity and other important metrics, the industry remains reluctant to invest in construction R&D. Other constraints for adoption include high fragmentation of project players and wide-ranging risk aversion (McKinsey & Company, 2017). Some of the currently implemented technologies including BIM software, AR/VR, drones, wearable safety devices, smartphone applications, and project planning programs have made significant changes to the project lifecycle. We are reaching a point in the productivity plateau where technology must be implemented into construction projects early if companies are to survive the changing work environment and attract a younger work force (Jones, 2018). A McKinsey Global Institute construction survey identified three interventions to break through the innovation blockade plaguing the industry: *1. Embedding innovation through the organization and across the value chain, 2. Strengthening the link between technology supplier and owners, 3. Improving risk sharing of new approaches* (McKinsey & Company, 2017). While there will always be a cutting-edge technology breaking into the construction scene, internal processes are found to be some of the most significant

barrier to adoption of new technologies (McKinsey & Company, 2017). Internal adoption factors are not within this scope but should be examined as a technology develops.

Innovation demands significant effort to overcome old systems through trial and error, time and finally integration. A study done on the adoption of information technology in an agricultural setting identified several factors influencing its integration. Which include general factors: political, economic, social and technological, as well as specific factors: customers, suppliers, competitors (Chieochan et al., 2000, Pheng et al., 2019). In addition to these factors, governmental and organizational influences affect adoption rate as well as level of expertise and technology performance metrics as indicated in (Pheng et al., 2019). (Gambatese & Hallowell, 2011) identified fear of change, lack of scientific significant recognition and lack of communication within innovative fields to be the most significant internal barriers. Organizational cultures open to new ideas have had favorable increases to innovation acceptance while closed, conservative organizations tend to resist change (Gambatese & Hallowell, 2011). However, the construction industry is not one organization and is highly diffused amongst designer, builders, suppliers, specialty trades, etc. These articles focus on the broad picture acceptance on technology. Industrial applications, individual organizational factors and other unforeseen aspects will impact adoption to varying degrees at varying rates. They provide a framework of general adoption for the 3DCP technology to be assessed against other technologies which have come before it. Adoption is a process and although the general and specific factors may change over time, the adoption process stays the same.

2.5.2 Technology Performance Metrics

Technological performance metrics are measurable means to gauge efficacy when in the field and are of paramount importance in early development as explained in article (Pheng et al., 2019). Utilized in a construction application, they can be factors which organizations use to assess the adoptability of a technology. These include cost, time, quality, safety and sustainability (Enshassi et al., 2009, Pheng et al., 2019). Other metrics can be applied but, for this analysis, they are the most widely applicable to 3DCP in its early stage of research.

The table identifies some of the technology performance metrics in terms of motivators for adoption and as an outcome of adoption (Gambatese & Hallowell, 2011). Cross examining the needs of the industry reviewed in section (2.2), with the performance metrics can allow for a more holistic understanding of the trending of the technology as its nascency does not yet allow for the metrics to be fully understood.

Table 2.2: Comparison of innovation benefits and motivators (Gambatese & Hallowell, 2011).

| Factor | % of respondents who identified the factor as a significant or higher motivator | % of respondents who identified the factor as a significant or higher benefit |
|-----------------------|---|---|
| Cost | 89 | 66 |
| Productivity | 80 | 71 |
| Quality | 83 | 80 |
| Competitive advantage | 85 | 90 |
| Market share | 59 | 48 |
| Safety | 65 | 63 |
| Marketing | 51 | 48 |
| New market | 52 | 57 |

Determined to be one of the most apparent factors to implementation and technological advancement was cost efficiency in the technology’s performance (Pheng et al., 2019). Along the same vein, is time savings and reduced man-hours which lead to decreased costs among the highest rated metrics. While improvements to cost and time hold much of the attention during technology advancement, quality is also a crucial determinant to success. It is also argued that quality should never be compromised by cost and schedule (Pheng et al., 2019). They should rather serve a complimentary roll in development of a safe and reliable product. This study shows safety was situated in the lower half of both categories, behind cost, time and quality (Gambatese & Hallowell 20,11). The safety metric sits below many of the others involving cost. Often deemed the most important value on a site, it can often be overlooked and undervalued when additional pressures enter the field. Although environmental sustainability is not situated in the results of the article, it has evolved into a topic of great concern. The new wave of construction technology is due and with it may come eco-innovative practices.

In all of the performance indicators from examined literatures (Enshassi et al., 2009, Pheng et al., 2019), 3DCP can be overlaid with these metrics and argued to be on the path to future implementation. As the technology must reach a functional level of efficiency in order to create

positive economic and environmental results. 3DCP must achieve some successes before other certain metrics can be attained. Section (2.4) discussed the many challenges facing its growth including material hardening properties, layer cohesion, scalability and others. The technical challenges of the technology must be addressed before mainstream adoption can occur and for industry adoption to take place. 3DCP is making great strides in its early years. Although not the aim of this study, the internal organizational and governmental factors should also be considered when deciding game-changing technology adoption further along in the field implementation phases. Field implementation of a functioning prototype is the next step in development and as processes begin to formulate and streamline, greater attention will be drawn for the on-site applications.

2.5.3 Field Implementation

Although 3D print elements can be created off-site or in situ, the analysis of this section focuses on the on-site potential. Later in the data analysis section (4.1.7), the technology will be reviewed in both contexts. The analysis would otherwise function as another review of precast technology and overlook the important interactions between the technology and the complexities of a construction site. According to article (Bos et al., 2016), the evolution of additive

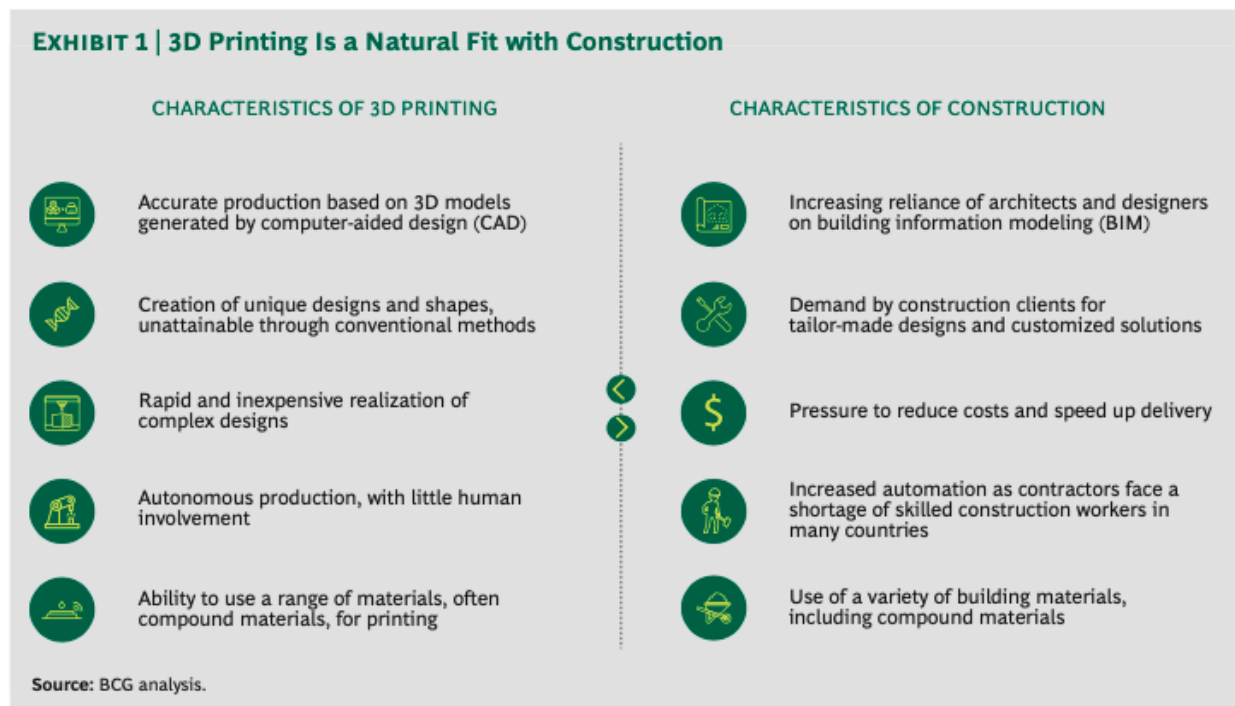


Figure 2.13: 3D Printing is a Natural Fit with Construction (The Boston Consulting Group, 2018).

manufacturing in construction can be observed to develop in either optimized production versus optimized performance via off-site versus onsite. Optimized production focuses on high output, low costs utilizing both on or off-site operations. Due to the housing shortage in China, Winsun, HuaShang Tengda and other companies such as Contour Crafting or COBOD, appear to be focusing efforts on this method of production. Optimized performance creates highly customized elements requiring high levels of detail and complicated geometries. Again, optimized performance can be utilized off or on-site and is researched by Contour Crafting, D-Shape, Total Kustom, CyBe, XtreeE and others previously mentioned in the prior sections (Wolfs, 2015). Although, off-site versus on-site applications can be pursued with both optimized production and performance, the printed element will likely dictate the location of printing. Modular printed housing is more likely to be printed in-place due to size restriction for assembly and transportation limitations. Architectural facades despite not being restricted by size would be more likely to be printed in a controlled facility to limit unforeseen site conditions and offer greater print precision.

In on-site applications, which is the primary topic in question for this study, literatures examine the effects and intricacies of field deployment. An instance of potential on-site deployment can be seen through a means of on-site facilities (Bock, 2015). These robotic on-site factories could provide greater control of the site conditions, material flow and organization. This provides improved control for all required prefabricated elements along with a few included benefits of on-site placements (Bock & Linner, 2016). Discusses the on-site impacts of a robotic factory, as it would compare to a manufacturing setting. The presence of the factory would create separate work environments and mitigate many logistical issues assuming complete separation and available site space (Bock & Linner, 2016). This method is being explored by many 3DCP companies which focus on the creation of single-unit homes. This creates a dedicated manufacturing area on the site with the potential to separate the hazards of the printer from the rest of the site. 3D concrete printing is doubly capable in on or off-site production, factory or field with the option of robotic arm or gantry style to best suit site conditions. Robotic arm printers are considered more mobile and adaptable to site conditions typically utilizing a 3-meter arm reach. One of the gantry printers used by COBOD can print dimensions 6.8 x 7.7 x 5.8 meters and is capable of on or off-site use, similar to the robotic arm, only with different set up

durations (COBOD International A/S). While these pieces of equipment by themselves can be comparable to traditional equipment, the interactions with site activities are what makes the implementation on-site another major driver for this specific technology's adoption. Interactions are untested, unpredictable and subject to unforeseeable variables, all while working on projects that are never exactly the same as the last. These in conjunction all may be detrimental to the element's quality and nearby worker health.

Another aspect of field implementation for 3DCP technology is the impacts on workers and worker perceptions of the automated presence. While the industry shifts to a more manufacturing-based production system, the labor force will shift from direct hands-on craftsmanship to technologically based tasks. The workers reactions of the on-site labor shift are another untested topic of discussion. Automation decreases the need for direct human labor and ultimately might be perceived as a threat to the existing work force. Labor resentment is not found as a performance metric in any of the literatures, however, it is an important consideration for every industry. Technical performance metrics gain much attention with early technology adoption and the potential benefits of its success. But for construction advancements, on-site integration is often overlooked and even more so the impact on the individual workers. Field deployment is an area yet to be considered in 3DCP technologies growth. Although field studies exist on construction robotics, 3DCP is unique in its methods and applications. Innovation has taken the spotlight for the technologies growth and has eclipsed a potentially crucial aspect to the success of its integration.

2.5.4 Outcomes of Integration

The omnipresence of construction concrete creates a gateway for widespread introduction into numerous industry applications across the world. 3DCP has completed its proof of concept through iconic structures by COBOD, Winsun and other major printing companies. They have shown the technology works but has a long road ahead in overcoming technical challenges, mix design specification and general industry acceptance. Notable benefits of the technology expected to propel innovation and relief to the industry include improved productivity via predictable outputs and streamlined manufacturing processes, increased sustainability and material efficiency via reduced material waste and greenhouse gas emitting activities, improved

worker safety & health via reductions in workers on-site exposed to hazards and reduce direct labor, and increased design opportunities via dimensional freedom and formwork restrictions. 3DCP is also poised to provide relief in the industry by way of addressing the global housing shortage via providing fast, inexpensive, replicable housing solutions, qualified labor shortage via a changing direction of technical skills, affordable material costs via design optimization and reduced non-value-adding activities and others yet to be realized.

Despite these widely anticipated beneficial outcomes, before they may be attained, barriers and enablers within individual entities play a significant role in adoption. Inconsistencies, barriers and technical challenges were generally found to pose the greatest challenge to 3DCP mainstream integration. However, general implementation of innovative construction technology examined in article (Gambatese & Hallowell, 2011), reveals that fear of change, lack of client recognition, lacking communication and fear of failure are some of the largest barriers to Innovation Generating Organizations (IGO's). In contrast, enablers to innovation implementation and diffusion were found to be internal communication and amount of funds available. The study also found that the potential outcomes of implementation with positive correlations of diffusion among manufacturers were improved quality, appearance of new markets and increased market share (Gambatese & Hallowell, 2011). Adoption of new ideas is the adoption of innovations. Where integration may be seamless for one organization, it may be impossible for another. The earliest examples of 3D printed structures can be seen with modular printed units and precast components utilizing gantry and robotic arm printers. Despite, on and off-site potential for both, testing in an uncontrolled field setting has yet to be thoroughly explored. The technology in theory has the ability for on-site deployment, but the integration among the field and all the unknown variable that come with it is a point of further research. Organizational integration and field implementation although pertaining to these two printers, are very different realms of consideration in the future of concrete printing adoption.

2.6 Research Questions

From the examined literature, several themes arose across previous works. The literatures showed current methods of concrete construction and their distinction from 3DCP methods in addition to similar up-and-coming concrete technologies competing with printed concrete. It

reviewed widespread issues affecting all sectors of the industry. It studied the intricacies of the 3D concrete printing systems and processes essential to success along with the challenges confronting its future growth. As there exists numerous studies on the previous topics of inquiry, the gap in literature exist between the on-site implementation and integration of the 3DCP technology through qualitative perspectives. The research methodology in the following chapter in this thesis will extract the themes of the previous literary sections to develop questions used to further the investigation of this innovative application. The research questions of this study guiding the interview and analysis process are as follows:

- What are factors that influence 3DCP integration on construction sites?
- What is being done in 3DCP development to ensure integration occurs?
- Why is the integration of this technology important for the industry?
- How will the integration of 3DCP change construction?

Chapter 3. Research Methodology

3.1 Study Design

The data collected by the author was made possible by participating in a research project based in Denmark. The author held a Visiting Researcher position at the Technical University of Denmark (DTU) from August 2019 until December 2019. DTU along with other research institutions and industry partners including architects, engineers, contractors, trade professionals, material suppliers, precast manufacturers and other member entities all collaborated on the “N3XTCON” research project. The project mission is to deliver the next generation of 3D concrete printers. Access to project partners allowed the author to gather perspectives on specific scopes of the project. Interviews also occurred in Seattle to include a comparative perspective on American practices and technology implementation. The data provided case specific information on the project which was used to both analyze general information on 3DCP as well as the Danish Research environment. This allowed the data collected to be from an in-progress research endeavor of the technology in question.

Interviews were conducted over the phone and in person. The total interview process began in October 2019 and continued through January 2020. Interviews completed between October-December were completed in Denmark over the phone or in person with N3XTCON project researchers and researchers with knowledge of 3D printing systems. Interviews conducted in Seattle were with participants not affiliated with the N3XTCON project. Interviews were obtained through the authors contacts from general contractors and through the University of Washington. Danish interviewees were selected based on their availability through the N3XTCON project. Interviewees affiliated with DTU were interviewed in person or over the phone within Denmark. A total of 19 interviewees encompass the data analyzed in section (4), 16 N3XTCON and three USA contractors. N3XTCON project specific information was obtained from the project proposal.

The interviews followed a semi-structured method in which the questions asked were taken from a list of questions assessing various topics around 3DCP technology, future outlook implementation. Question lists were divided into three groups. Group 1, *N3XTCON Project*

Questions, group 2, *Standard Questions* and group 3, *Industry Questions*. Question groups are noted N#, S# or I#. N3XTCON questions were those asked to N3XTCON project team members about the project, their involvement and their perspectives. Standard questions were those asked to N3XTCON and non-N3XTCON interviewees about general industry questions and general 3DCP technology. Industry questions were those asked to interviewees in Seattle on general technology implementation, general robotics and 3DCP information. The questions were sorted into three groups and further broken down into topical areas derived from literatures which include: 1. *N3XTCON Project Management*, 2. *Respondents Field Application*, 3. *Competing Practices*, 4. *Industry Issues*, 5. *3DCP Systems*, 6. *3DCP Challenges*, 7. *On-site/Off-site Applications*, 8. *Field Integration*. Table 3.4 displays a topical matrix of these questions and research areas. In order to maintain relevance, questions were asked to participants who held a background in the topic in question. For example, N3XTCON team members with a design background would be asked about their perspectives on design, structural engineers about reinforcing and trade professionals about technical aspects. Information on participants background was acquired prior to the interview in order to prepare relevant questions.

Questions were catered to interviewees based on the authors understanding of the interviewee's background. Between 3-8 questions were asked from a total pool of 20 for Danish interviewees and 10 for USA interviewees. Interview lengths ranged between 17-36 minutes. The scripted questions were occasionally followed up with clarifying questions to expound the prior response. The interviews were recorded using a computer microphone or cell phone with verbal acknowledgement of recording prior to interview. Interviews were transcribed to a written outline and a thematic analysis was conducted across interviewees and question areas determined from the literature review section.

3.2 Background & Rational

Interviews were the preferred method of data collection for this study due to a number of factors.

Access to Interviewees

Exposure to N3XTCON partners allowed for firsthand interviews to be obtained. Direct ideas from researchers and industry professionals can be more valuable of a resource than impersonal surveys or experiments on irrelevant research areas.

Field of Study

The construction management field is not one which may be easily encapsulated by quantitative data alone. The nature of construction science is complex in the relationships of people, environments, materials, economic markets and a host of other academic fields. Studies in the construction management field include both qualitative and quantitative analysis but trend away from substantial computational data.

Number of Interviewees

Although the N3XTCON project involves six industry partner classifications, the number of respondents was limited to 19. Interviewees in Seattle are used to assess a specific aspect of the research question and may not hold sufficient knowledge of 3DCP technology to warrant extensive questioning. Thus, a survey was not conducted as the sample would be too small.

Danish Case Example

The analysis of the interviews was through the lens of a Danish research environment ongoing study of the 3DCP technology. The interview questions explored the project's operational focal points which will be analyzed with the interviews to answer the research questions.

Much of what is published in existing literature is that of experimental trials of 3D concrete printing technical capabilities and challenges. What the author's approach holds that other studies have yet to incorporate are the methods commonly used with interviews and qualitative analyses. The opportunity to integrate a 3DCP example of an ongoing research project will reveal the inner workings of how advancements in the technology might come about beyond the numerically driven data. It provides a qualitative analysis of a project typically approached utilizing quantitative methods. The result of this method and overall outcome of the study will hopefully expand perspectives of the technologies advancement through managerial practices and interdisciplinary methods sharing.

With this new approach comes limitations which must be considered in order to validate the findings. These limitations include the following:

Early Project Status

The N3XTCON Project began in 2019 and will continue until 2022 and beyond. Thus, information at this stage is mostly speculative for general applications and is subject to change.

Country Specific

While numerous organizations across the world are advancing 3DCP, the Danish example will have to provide generalizable insights and may not sufficiently match findings of other.

Question Limit

Questions were determined in advance of the interview based on the authors understanding of the interviewee's background. Thus, the author was required to deliberate upon topics expected to produce the most viable information. From a total of 30 questions, it was not reasonable to ask participants to answer all the questions.

Question Categorization

Interviews were semi-structured which allowed the process to incorporate questions to be developed along the way to fill gaps in knowledge. This, however, created a non-standardized question base which cannot allow every response to be reliably compared across all interviewees.

With these limitations also comes the strength of this qualitative approach. These strengths include the following:

Interviews with Professionals

Interviews of individuals with knowledge of the technology and related disciplines are the best sources of information when looking to future advancements and applications.

Interview Flexibility

Semi-structured interview questions can be followed up on related topics and lead to new information not previously known before the interview.

Comprehensive Example

The study example of the N3XTCON project allows not only a look at the technology but the direction of 3DCP as it develops through a working process, giving access to more sources than just project outcomes.

Answer Variability

While there were limitations, asking different questions to different interviewees allowed a wider range of answers to be explored beyond just the topic in question.

What this study provides is a new realm of inquiry around the development of digital concrete. Studies are in progress examining the opportunities and barriers through a very narrow scope; primarily around technical aspects and general technology performance. Studies typically utilize quantitative analyses in the field of engineering and material sciences. However, for technology to be useful, the end users should be included in the research process to ensure it becomes a usable tool for the industry. In the field of construction management, qualitative observations may be better suited to the intricacies of project partner interactions and industry acceptance of 3DCP technology. This study blends existing technical sources of literature with interviews from professionals achieving the best of both worlds. While there are limitations regarding the design and execution of this study by means of the interview process, early project phase and individual country example, the strengths of the study prove beneficial in the overall advancement of the practice. By utilizing a case example, the industry can look to the methods of the N3XTCON project for insight as to the direction of the Danish example and expanding the academic community. Interviews provide an underutilized form of data which can provide information in a manner not typically reviewed in the early stages of a technology's growth. However, making industry professional knowledge available may provide steppingstones to further breakthroughs through unconventional methods of research.

3.3 Interview Questions

The following tables contain all of the interview questions used in this study. It is important to display these questions as they provide context for the remaining chapters and guide the discussions. As previously mentioned, the questions were derived from existing literature and form the basis for the thematic analysis. The question groups include: Group 1, *N3XTCON Project Questions*, Group 2, *Standard Questions* and Group 3, *Industry Questions*. Question group notations include N#, S# or I#.

Table 3.1: Group 1: N3XTCON Project Questions

| Question Notation | | Question |
|-------------------|------|---|
| N1 | 1 | What distinguishes the N3XTCON project from other 3DCP projects? |
| N2 | 1, 2 | What is your partner role in the development of the N3XTCON project? |
| N3 | 2 | How can 3D printed concrete revolutionize your field/trade? |
| N4 | 5, 7 | With the robotic arm printer targeted for the prefab applications and gantry for on-site, do you see these printers used interchangeably? Or exclusively? |
| N5 | 7, 8 | During on-site operations (Mobilization/Printing/Disassembly), what safety, performance, site logistics and overall environmental factors must be considered? |
| N6 | 5, 6 | How does the N3XTCON Project plan to address the reinforcement strategies issue? What are things to consider? |
| N7 | 2, 4 | What are your methods in the N3XTCON project for optimizing sustainability of designs? |

Table 3.2: Group 2: Standard Questions

| Question Notation | | Question |
|-------------------|------|---|
| S1 | 2 | How will structural designs and building standards change as a result of 3DCP? How do 3DCP cater to existing standards? |
| S2 | 5, 6 | In what aspect do you anticipate the most significant upcoming 3DCP breakthrough being? |
| S3 | 7, 8 | What are the driving factors and barriers for 3DCP on-site implementation? |
| S4 | 4 | In what industry or sector do you see 3DCP having the most success? |
| S5 | 8 | Where do you see the 3DCP being integrated first? Why? |

| | | |
|-----|------|---|
| S6 | 4, 8 | How do you see the labor force being impacted by 3DCP implementation? |
| S7 | 7 | What are internal project level considerations for 3DCP technology use on-site? |
| S8 | 4, 8 | How would widespread 3DCP adoption impact material supply and demand? |
| S9 | 7 | Can 3DCP be reasonably deployed on-site with all the variables in affect? Why? |
| S10 | 4 | How do you see 3DCP addressing construction industry issues such as stagnant productivity, sustainability, labor/skills shortage, etc...? |
| S11 | 6, 7 | How might reinforcing strategies change between robotic arm and gantry printers? Between on or off-site applications? |
| S12 | 3 | How will Denmark specifically be changed by 3DCP advancements in precast technology and large-scale prints? |
| S13 | 2 | How will 3DCP research revolutionize concrete technology as a whole? |

Table 3.3: Group 3: Industry Questions

| Question Notation | Question |
|--------------------------|---|
| I1 | 2, 8 At your position, are you able to make decisions on integrating new and innovative construction technologies? If so, what are deciding factors? |
| I2 | 2, 8 From a project management and site logistic perspective, what are things to consider when deciding whether or not to adopt new tools/equipment into a construction process? |
| I3 | 2, 8 From past experience, what have been successful examples of new tech implementation? |
| I4 | 2, 8 Have your previous projects had opportunities to implement any new technologies? What were the observed benefits/setbacks if any? |
| I5 | 8 How might you get the field onboard with accepting new technology? |
| I6 | 3, 8 Would you consider using construction robotics in the field? Why or why not? |
| I7 | 3, 8 How do you project the future of construction field robotics in the next 10 years? |
| I8 | 3, 5 Can you explain CNC and how it differs from 3D printing? |
| I9 | 3, 5 Do you believe 3DCP will soon compete with the existing US precast industry? |
| I10 | 3, 8 How might 3DCP assimilate into the industry with current virtual/design and construction methods? |

Table 3.4: Interview Question and Topical Matrix

| Question Notation | Interview Question Areas | | | | | | | |
|-------------------|----------------------------|-------------------------------|---------------------|-----------------|--------------|-----------------|--------------------------------|-------------------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| | N3XTCON Project Management | Respondents Field Application | Competing Practices | Industry Issues | 3DCP Systems | 3DCP Challenges | On-site/ Off-site Applications | Field Integration |
| N1 | RI | | | | | | | |
| N2 | RI, AD, SD, S, TP | RI, AD, SD, S, TP | | | | | | |
| N3 | | RI, AD, SD, S | | | | | | |
| N4 | | | | | TP | | TP | |
| N5 | | | | | | | RI, TP | RI, TP |
| N6 | | | | | RI, SD | RI, SD | | |
| N7 | | AD | | AD | | | | |
| S1 | | AD, SD | | | | | | |
| S2 | | | | | RI, AD, S | RI, AD, S | | |
| S3 | | | | | | | RI, TP | RI, TP |
| S4 | | | | RI | | | | |
| S5 | | | | | | | | TP |
| S6 | | | | RI | | | | RI |
| S7 | | | | | | | RI, AD, TP, C | |
| S8 | | | | RI, S | | | | RI, S |
| S9 | | | | | | | RI, TP | |
| S10 | | | | RI, TP | | | | |
| S11 | | | | | | RI | RI | |
| S12 | | | RI, AD, SD, S | | | | | |
| S13 | | RI | | | | | | |
| I1 | | C | | | | | | C |
| I2 | | C | | | | | | C |
| I3 | | C | | | | | | C |
| I4 | | C | | | | | | C |
| I5 | | | | | | | | C |
| I6 | | | C | | | | | C |
| I7 | | | C | | | | | C |
| I8 | | | C | | C | | | |
| I9 | | | C | | C | | | |
| I10 | | | C | | | | | C |

The table depicts the questions against the relevant topic and which interviewee classification was asked.

Interviewee Classification

RI - Research Institutions
S – Supplier

AD - Architectural Designer
C – Contractors

SD - Structural Designer
TP - Trade Professional

Chapter 4. Data Analysis and Discussion

In this section, the N3XTCON project information will be reviewed to provide a basis for analysis when interpreting the interviews. The information gathered from the Danish interviews will be assessed based on a thematic analysis structure of the interview question areas: *1. N3XTCON Project Management, 2. Respondents Field Application, 3. Competing Practices, 4. Industry Issues, 5. 3DCP Systems, 6. 3DCP Challenges, 7. On-site/Off-site Applications, 8. Field Integration*. The themes extracted from existing literature were used to develop the interview questions. The overarching themes will guide the questions and will be cross-examined with the respondent's field of expertise. While questions can be categorized by the interview areas 1-8, responses to these questions may diverge into other areas providing overlapping concepts. In the later sections, the implementation of the 3DCP technology will be analyzed across all factors to discuss the findings of themes and projected outlook for the technology. The results of the American interviewees will then be reviewed to provide supplemental content and create a discussion between the two countries practices and tendencies in emerging technologies. Finally, a discussion of all sections will close the chapter. Bolded text indicates key findings of the research. The overall analysis process will be approached by means of an exploratory analysis to understand current trends and trajectories. The information in this analysis section reflects the activities of the N3XTCON project as the author interpreted them at the time of the interviews. As the project will continue through 2022, research activities will evolve, adapt and may lose contemporary relevance.

4.1 Thematic Analysis

The interviewees involved in this research come from a diverse range of research areas and professional backgrounds. The interviewee classifications include: *Research Institutions (RI), Architectural Designer (AD), Structural Designer (SD), Supplier (S), Contractor (C) and Trade Professional (TP)*. The interviewees within each classification can be seen in *Table 4.1: Interviewee Classification and Questions List* along with a graphic of the breakdown of classifications in *Figure 4.1: Interviewee Classification Percentages*. The interviewees' organizations are listed and denoted by *DTU, DTI, SDU, AP, BIG, COB, CRH, HLA, NCC, HSW* and *TC* in the table and text. Other partners outside of those listed, are involved in the project but were unable to be contacted for the interviews. The contractor group from the N3XTCON

interviewees also doubled as structural designers. Their responses will be classified as the (SD) group. In the following section (4.2), USA contractors will be introduced to the analysis as will the contractor classification. In the following headings, a notation (#) will reference the interview question areas from *Table 3.4: Interview Question and Topical Matrix*. These notations can also be seen in tables (4.2) and (4.3) where the topics are shown to display the areas of inquiry derived from the literature review chapter.

Table 4.1: Interviewee Classification and Questions List

| N3XTCON Project Interviewees | | |
|---------------------------------------|-----------------------|---|
| Organization | Classification | Questions |
| Technical University of Denmark (DTU) | RI | N1, N2, S3, S4, S9, S10 |
| Technical University of Denmark (DTU) | RI | N1, N2, S3, S9 |
| Technical University of Denmark (DTU) | RI | N2, S4, S6, S8 |
| Technical University of Denmark (DTU) | RI | (Questions for 3D Printing background only) |
| Technical University of Denmark (DTU) | RI | N1, N2, N6, S6, S11 |
| Danish Technological Institute (DTI) | RI | N2, S7, S4, S8, S10 |
| Danish Technological Institute (DTI) | RI | N1, N2, S2, S12, S13 |
| University of Southern Denmark (SDU) | RI | N2, N3, N5, S7 |
| Aalborg Portland A/S (AP) | S | N2, N3, S2, S8, S12, |
| Bjarke Ingels Group (BIG) | AD | N2, N3, S1, S2, S7 |
| Bjarke Ingels Group (BIG) | AD | N2, N3, S7 |
| COBOD International (COB) | TP | N2, N4, N5, S3, S5, S10 |
| COBOD International (COB) | TP | N2, N4, N5, S3, S9, S7 |
| CRH Concrete (CRH) | SD/C | N2, N3, N6, S1, S12 |
| Henning Larsen Architects (HLA) | AD | N2, N3, N7, S1, S12 |
| NCC Denmark (NCC) | SD/C | N2, N6, S1, S12 |
| Industry Interviewees | | |
| Turner Construction (TC) | C | I6, I7, I8, I9, I10, S7 |
| Howard S. Wright Construction (HSW) | C | I1, I2, I3, I4, I5, I6, I7 |
| Howard S. Wright Construction (HSW) | C | I1, I2, I3, I4, I5, I6, I7 |

The project “N3XTCON” involves 11 total partners from all levels of the technology’s lifecycle whose ultimate goal in the project is to deliver the next generation of 3D concrete printers. Architects, engineers, contractors, suppliers, manufacturers, research institutions and other partners are all involved and assigned to specific work packages in the project. The packages align with the partners’ primary specialization among robotics, concrete mix design, mix rheology, field applications, etc. As there are many milestones to be achieved over the course of

the next few years through 2022, the main goals as stated in the project proposal are advancements in:

1. A simulation tool that predicts the print process based on models from 3DCP print parameters and the evolution over time.
2. Second generation 3D concrete printers based off of the robotic arm and gantry style printers, which can be utilized in upsized industrial applications.
3. Design guidelines to govern reinforcement strategies as the basis for future generations of custom 3D concrete structures.
4. Guidelines on mix designs and material characterization.

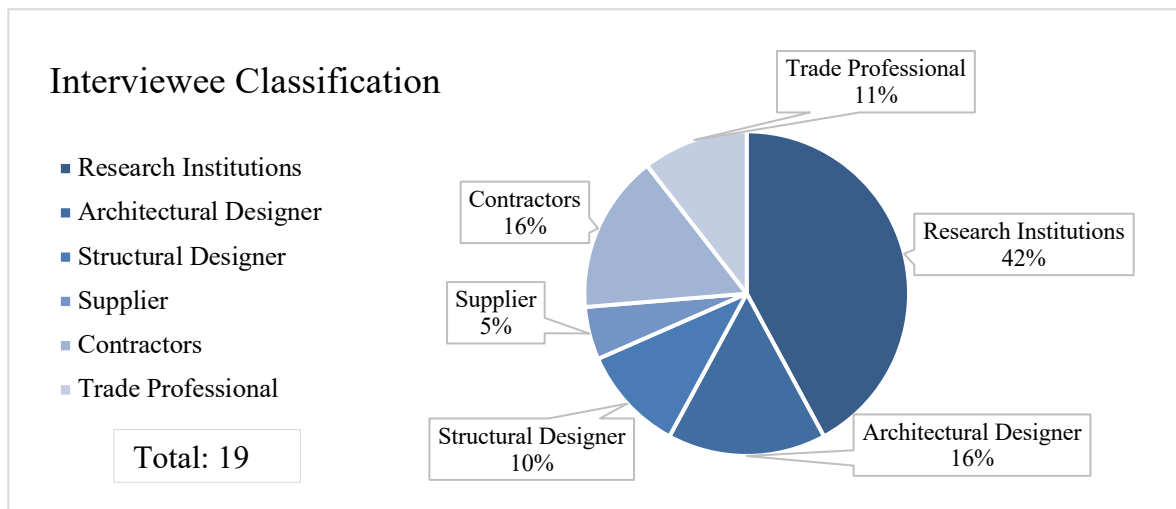


Figure 4.1: Interviewee Classification Percentages

The N3XTCON goals served as a resource for the creation of many of the interview and overarching research questions of this study. The aims of the project have specific processes in place to ensure these goals are met. Thus, individual scope is more redefined. As opposed to this study whose purpose identifies more closely with an exploratory analysis.

Table 4.2: N3XTCON Interview Question Areas

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|----------------------------|-------------------------------|---------------------|-----------------|--------------|-----------------|--------------------------------|-------------------|
| N3XTCON Project Management | Respondents Field Application | Competing Practices | Industry Issues | 3DCP Systems | 3DCP Challenges | On-site/ Off-site Applications | Field Integration |
| √ | √ | √ | √ | √ | √ | √ | √ |

4.1.1 N3XTCON Project Management (1)

At the beginning of each interview for this study, questions N1 and N2 were asked of the respondents. These questions served as primer questions to understand the interviewees perspectives on the management of the project as well their individual and partner roles. Question N1 was directed towards interviewees from research institutions as they have the most research experience among the other interviewees. Additionally, some members from research institutions are Project Manager. This question builds upon the background of the project in a manner that only the respondents can explain in their breadth of experiences. In conjunction with N2, this series combines personal involvement of the partners specific work areas and is asked of everyone involved in the N3XTCON project. Providing context to the technology in question is essential to validating the responses. This analysis is not only a review of interview responses but also assesses how the project has and will contribute to the greater endeavor.

What emerges from the response as to the distinctiveness and strength of the N3XTCON project is primarily that of the multi-disciplinary approach to innovation through the inclusion of all competencies from all levels of the production chain. Furthermore, this collaboration allows for increased opportunities for shared knowledge and industry input. As stated by a DTI researcher, it is the goal to upscale this technology for industrialized use. An additional comment made by another interviewee was the lack of knowledge surrounding the status among other 3DCP projects as everyone is still in the learning process at this stage. The results of question N2 provide an array of information surrounding the individual goals of each partner as well as the holistic ambition of their discipline. The results primarily aligned with each of the aims defined in the project work packages which amount to eight in total over the course of the project. Each work package involves several partners and strives for different outcomes in pursuit of the greater project goals explained in section (4.1). At this early stage of the project, interviewees appear to be directing most of their efforts on several areas including the development of a functioning model to predict print behaviors, the trials of material property parameters, the creation of sustainable designs and improvements to a new printing system. These aim to align with the project timeline and will continue to evolve into the remaining packages as the project progresses. The next section (4.1.2) will review the responses to question

N2 in greater detail, examining the specific partners ambitions as it pertains to further project development.

4.1.2 Respondent Field Application (2)

As mentioned in the previous section, responses to questions N2 were answered on the basis of work package involvement predetermined by the project. Questions N2, N3, N7, S1 and S13 revealed prospective forecasts of discipline specific traits of 3DCP. The classifications of each of the respondents and, within each classification, provides a variety of responses which is expected.

Research Institutions

Responses from this group were divided into the goals associated with print modeling, reinforcement strategies, material characterization and robotic programming, all of which align with the partners' core competencies. At each of the research institutions, the ambitions contribute to overall strength of the process for the printer to successfully print a material without failure.

Architectural Designers

The architectural design group responses reverberated a consistent theme across the two design firms: sustainability. The designers' goals are to formulate sustainable designs for the printer while maintaining consciousness of other systems and limitations. Although through various approaches, material optimization and the reduction of waste through the project lifecycle is of the utmost priority in not only the architectural design group but also mentioned by several partners.

Structural Designers

The responses from the structural designers focused mainly on the work packages tasked with the integration of reinforcing strategies as well as the eventual mock-up precast element included as one of the project deliverables.

Suppliers

The supplier provides materials to other partners as well as recommendations for the binder systems used with the current activities on the project in addition to the potential for a new cement types specified for the printer.

Contractors

This response group is not currently active at this stage of the project. The structural design group doubled as contractors for this section.

Trade Professionals

The primary goal of the printing company as well as the entire project is to deliver the next generation of 3D concrete printer. The trade professionals group specializes in the gantry printing technology specifically. **Although, their efforts revolve around improving the entirety of the printing process.**

The results from the remaining questions provided greater depth into specific industry applications and trajectories. Structural and architectural designers responded with outlooks pertaining to the technologies greater design freedom through new geometric possibilities in transcending traditional shapes of columns, beams and walls. As stated by several designers, it is hard to compete with a precast wall (CRH). **The context in which the designers provided their position in design freedom was primarily in comparison to the precast industry by way of creating unique building elements as supplemental components with the ambition to progressively increase structural presence into entire structures.** With this hopeful outlook comes the concern of the majority of designers that the reinforcing and building codes may negate significant progress unless included in the early stages of development, especially for applications of entirely unique design. These concerns will be addressed further in section (4.1.4). **Research institutions, contractors and suppliers generally agreed that the 3DCP would not necessarily revolutionize their respective field or the construction industry as a whole. Rather it is seen as a supplemental tool to allow for new construction methods but not immediately as a staple practice.** As competing methods are strong, the technology will

likely stand in as a niche technology until the life cycle cost is analyzed and technical challenges are overcome.

Responses in this section range widely due to the interviewees area of specialization. The results display a separation in outlooks partly in the specific question asked as well as from those respondents focusing on future applications versus practical challenges of today. Similar to section (4.1.1), these questions prime the remainder of the interview for more refined questioning. They allow partner perspective while including project specific points into the responses. Results of the USA contractors in questions I1-I10, spread across the interview areas of interest, will be reviewed in section (4.2).

4.1.3 Competing Practices (3)

In the section (2.1) of the literary review, the author examines two of the most common concrete construction methods of today. In this section, precast methods were omitted from the section due to 3D concrete printing's on and off-site capabilities, essentially serving as a precast practice. In this section of the analysis, the precast industry is reviewed in the context of a competitive practice as well as its own method of 3DCP. This distinction is important to understand as the Danish construction industry invests heavily into traditional precast methods. It is important to recognize current processes for concrete construction as they all provide unique products for specific applications. As the field of construction is vastly diverse among sectors and structures, its applications are essential points of evaluation in 3DCP technologies eventual emergence onto the construction stage.

The results from the interviews in this section indicate that existing precast industry was overall determined to be the greatest competitor to 3DCP technology. In the context of the study, the precast industry may be defined as the off-site casting of traditional wall, column, slab and custom elements. As many of the attributes involved with 3D concrete printing can be overlaid with traditionally prefabricated building components but at a higher cost, the shift in practices is expected to be slow. Interviewees did not see significant encroachment into the established precast market share as it is not yet optimized to compete. Much of the competition confronting deployment are from not only parallel practices but from within the same concrete innovation

field. There exist methods stated in literature review section (2.3.2) on concrete innovation methods also stepping onto the scene. But for the sake of this study, COBOD trade professional identified a distinction between players in the 3DCP field. From within the Contour Crafting style of 3D printing exist companies like CyBe, XtreeE and Baunit, which focus on the customizable, off-site applications typically utilizing a robotic arm style printer allowing for greater precision within a smaller print radius. Then there are companies including Icon, Winsun and COBOD, which focus on the up-scaled, on-site application typically utilizing a gantry printer for more cost-efficient, larger-scale production. **These two styles of production have emerged as two distinct methods of 3DCP expected to propel the industry forward. Both printers are expected to compete in structural and architectural precast settings but are far from optimized.**

From the Danish example of question S12, the country was established to have a strong traditional precast industry. It is estimated that ~80% of houses in Denmark include precast components (DTU). As predetermined in prior studies, the two primary applications will be in prefabricated components (off-site) and in situ structures. As Denmark is the host for this study and as indicated by research institutions respondents with this great dependence on prefabricated building components, one of the outcomes for the N3XTCON will be an off-site custom printed component to serve as a mock-up. **However, the Danish market would likely not be the focus of 3DCP housing but rather the customizable components would serve as a supplemental option for customization of unique features. Direction of similar industrialized countries may be apparent in the 3DCP industry trends towards highly custom components as well as simple geometries of in situ printing.** Both are dominated by the traditional prefab practices

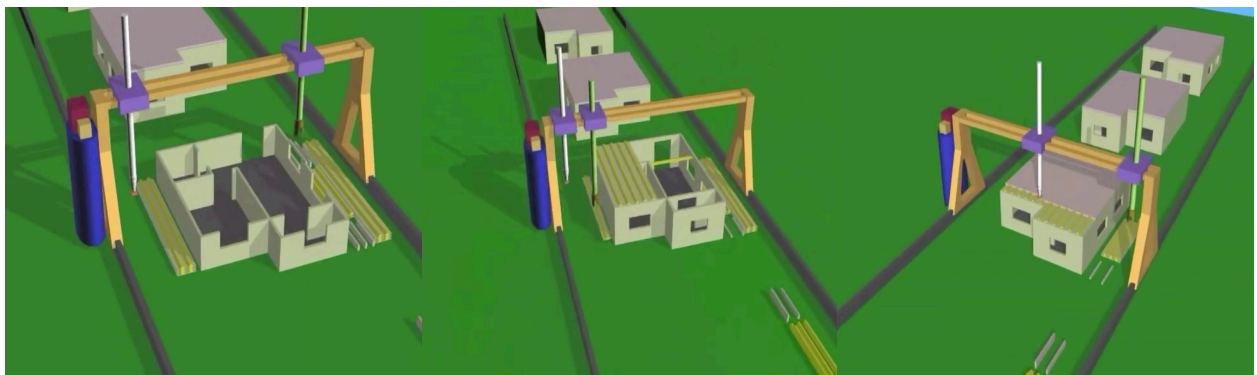


Figure 4.2: Contour Crafting building construction clips (contourcrafting.com/building-construction).

in Denmark. However, there are still many questions as to the extent it may impact Denmark and other industrialized countries without the need for fast and rapid housing as such a niche technology. In the next section, the on-site perspective for larger scale housing construction will be examined which is also an outcome of the project's efforts.

4.1.4 Industry Issues (4)

The industry issues addressed in this section of the analysis were guided from the previous research found in section (2.2) of the literature review. Although previously determined to hold promise in addressing the areas of concern, this section provides insight on the partners' opinions on how 3D concrete printing technology will benefit numerous industries in its eventual field implementation. The result in this section provide first-hand perspectives of researchers and professionals which allow for ambitious applications through their respective fields.

Productivity, Labor/Skills Shortage, Worker Safety & Health, Housing Shortage and Sustainability were all addressed in the context of this technology. These specific topics were guided by the author's questioning as they presented themselves as some of the most prominent concerns in the industry over the past years. Responses in this section were primarily derived from questions N7, S4, S6, S8 and S10. Each of the industry issues from section (2.2) will be reviewed in the context of the capabilities and limitations of 3DCP for addressing these widespread industry issues.

Productivity

Productivity in the construction industry is widely considered to be trailing far behind manufacturing, agriculture and related sectors. Examined in section (2.2.1), productivity is an umbrella term which is affected by numerous factors of production. In the context of the N3XTCON project, it is not necessarily seen as a primary outcome of this research. All interviewees agreed upon the potential for improved production output of 3DCP once processes become more robust. This is in part due to the reduced labor cost of the technology largely coming from the omission of formwork in the production lifecycle. **In the context of large-scale on-site printing, the trade professionals and research institution groups expressed concern for productivity in two areas: 1. The inability to be cost efficient by only completing one construction activity and 2. Material use and placement processes are not optimized to be**

competitive. Responses from the interviewees have expressed that while the production of the concrete structure will bring about cost savings, the numerous other construction activities will remain with their traditional methods of installation. Trades involving MEP, windows, doors, insulation, plastering and painting will need to adjust their practices to this new structural type. Methods of combining these processes are currently being explored in order to streamline more construction activities to allow for greater productivity potential (DTI). The second productivity concern arises from the nascency of the technology. Large amounts of cement are being used in lieu of the aggregates, driving costs up. The overall systems simply are not yet to a stage in which it can compete with existing practices. While both issues will likely be overcome as the systems become more streamlined, they present one of the biggest challenges to integration as cost stands to be the number one consideration of technology adoption amongst companies.

Labor/Skills Shortage

Question S6 directly addressed the concern with the labor and skills shortage. It was determined from prior studies that there is a shortage of qualified skilled labor and that 3DCP as an automated process has the potential to ease the burden felt across numerous industries. The researchers group determined that while 3DCP and the greater field of construction automation might benefit productivity and safety, there will remain the possibility of resentment of workers losing their jobs. In other industries when automation and robotics are implemented, the labor requirement will go down. It was seen in car manufacturing with the assembly line and thus less workers were needed (DTU). **What emerges is not a total removal of jobs but rather a shift in skills. It rather allows the job to be completed using less manual labor requiring improved technical skills with decreased exposure to risky work (COB).** Trade professionals and researchers agree that that the replacement of jobs by machines is an inaccurate depiction of the process's evolution. Discussed in a later section (4.1.5), is the challenge of worker skill shifting and the eventual challenges to adoption.

Worker Safety & Health

In general, N3XTCON interviewees did not foresee extensive benefits to worker safety and health from the applications of 3D printing technology. Discussed in greater depth in section (4.1.6), the COBOD printers do include safety measures into the technology. However, the

primary ambition of its deployment is not explicitly stated to benefit worker safety despite its potential for indirect improvements that arise from integration.

Housing Shortage

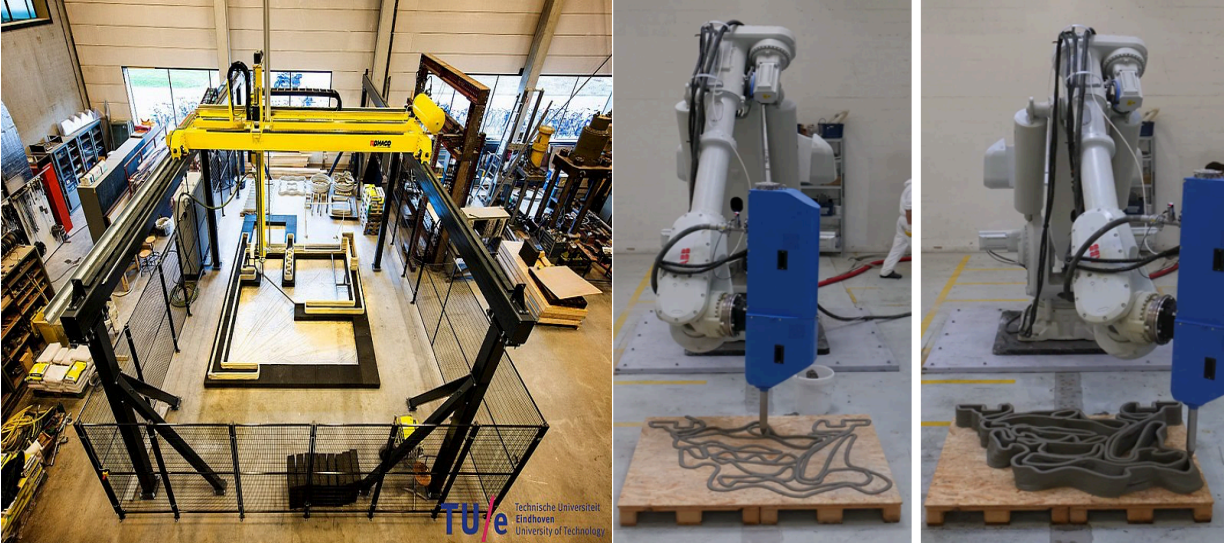


Figure 4.3: Gantry printer at Eindhoven University of Technology (tue.nl/en/research/research-groups/structural-engineering-and-design/concrete-research-areas/3d-concrete-printing/photo-gallery/).

Figure 4.4: 3D printed artificial reef by XtreeE (xtreee.eu/project-rexcor-artificial-reef/).

Over the course of the interviews, it was made clear the applications of 3DCP technology would likely take hold in two industry sectors: custom precast components and housing. Section (2.2.4) explains the global need for affordable housing is a humanitarian crisis. It further explains 3DCP's potential for providing relief. The divergence between printing companies in their market aim between precast component or upscaled structures has also been discussed. While not explicitly stated, COBOD utilizes the gantry style printer and has directed much of its resources in the pursuit of upscaled structures. It can be inferred that with such great demand for affordable housing and the possibility of 3D printers to produce desired houses, COBOD is likely to enter the international housing arena. **Responses from the researcher group revealed while there are two paths diverging for the technology to embark down, the housing sector will likely see success first and in different global regions.** This is in part due to the current process of printing the shell of the formwork and casting the elements and reinforcing inside. Conventional reinforcing results in conventional structures conforming to existing standards. Thus, the end product is more easily approved for structural use as the printed element serves only as the formwork. (DTI). Additionally, large-scale printed structures originally were anticipated to take

hold in developed countries due to high labor costs. They are instead more likely to be found in developing countries in need of fast and rapid housing (DTI). This also touches on the previous section and question S12 where Denmark and other industrialized countries will likely show a preference for custom components versus standardized geometries. From between the current market options, developed countries will likely be seen with customizable components integrated into their buildings rather than full scale structures of housing.

Sustainability

Sustainability reoccurred throughout the interviews without the author's direction of the question. It can be seen to be of utmost concern to many of the project partners, with and without the work package goal designation assigned in the project. Sustainable outcomes through reduced material consumption, reduced construction waste and reduced emissions from material transportation were the most common themes across all classification of partners.

From all partner groups material optimization was determined to be the primary sustainable feature of 3DCP technology. In the traditional method of concrete construction and precast, structural members are cast in simple geometries in order to meet a loading requirement. It also is most cost-efficient to cast in standard formwork. Thus, conventional columns, beams and slabs are over-designed for the sake of ease in constructability. The 3DCP process overall, reduces material where it is not required in addition to the reduction in waste from unused concrete. But what makes 3DCP technology so attractive is the absence of formwork and the waste generated from traditional wood forms and CNC custom manufactured forms for limited use. However, this omission of formwork affects several other facets of the technology's performance.

The absence of formwork creates the increased dependency of material performance. Cement content is sizably increased to allow for adequate stiffness and strength to develop as layers extrude. As explained in section (2.2.5), cement production contributes significantly to global CO₂ emissions. The dilemma now stands as improved material optimization at the cost of increased cement content. Life cycle analysis are in progress as the to 3DCP's CO₂ footprint as well as the energy, light and heat loss building performance (DTI).

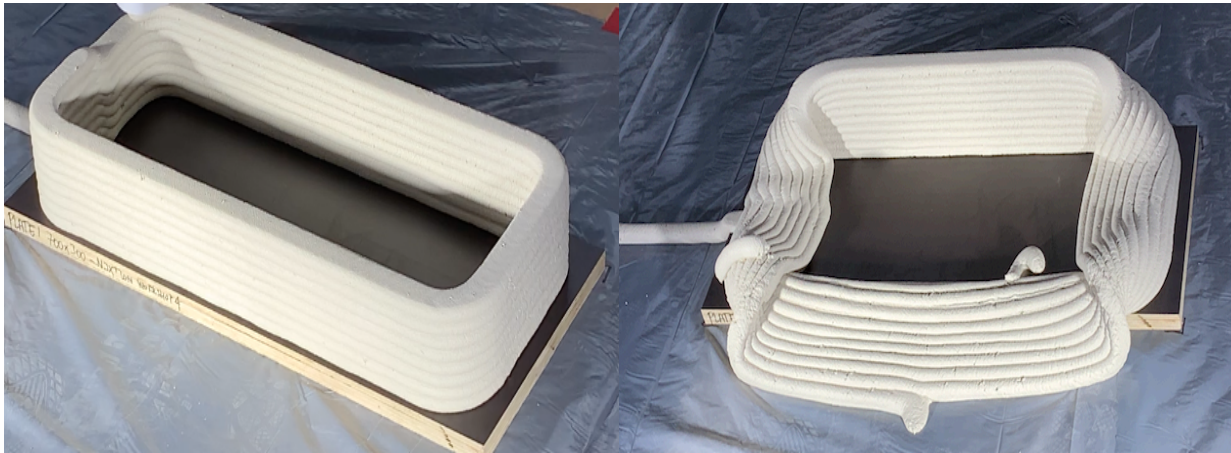


Figure 4.5: A test print at the Danish Technological Institute (Photo by author).

Responses to question S8, involved similar sustainability implications pertaining to the transportation of printing materials. It was determined that in order for designs to be successful, mix designs require admixtures and specialized cement, typically purchased from printer manufacturers. For companies involved in the export of printers globally, the shipping of specific materials would likely negate any emission reductions at high costs. Thus, print companies should partner with local producers for reduced transportation emissions (DTI). For future application, acquiring concrete materials may lead industries to rely more on recycling of materials beyond just cement optimization. This will be challenging for 3DCP as reused materials have not been tested in the process but as printers increasingly become capable of printing with larger aggregates, reuse might become a staple practice in material acquisition (AP).

The response from all interviewees indicate that the five industry topics previously discussed can be positively impacted from the eventual deployment of 3DCP technology. It is essential to gather all partner inputs on this variety of issues as their realms of expertise will undoubtedly be useful in addressing these problems. It is teams like these that propel emerging technologies forward. Collaborative, multi-disciplinary groups with a unified direction for growth are the projects which drive innovation. While there is much work still to be done, these industry issues serve as metrics in which the technology can be measured to meet to and surpass expectations.

4.1.5 3DCP Systems & 3DCP Challenges (5)(6)

During the interview process, every interviewee provided a breadth of technical information pertaining to their work in the N3XTCON project. For this section of the analysis, each group's responses on both technical systems and challenges will be reviewed. Although previously reviewed in separate literature sections, the challenges and technical information overlap significantly and would better serve the analysis in a joint piece. Questions N6 and S2 pertain to both topical areas with N4 and S11 touching on either/or. Through this study, responses will reveal project level challenges as well as technical challenges confronting the field as a whole. Limitations serve as an important reminder that the ambitions of research must be kept in check by realistic discoveries. As the technology is moving forward rapidly, the future outcomes and expectations of the partners are included in this section to provide a possible direction for the industry research as the technology overcomes these challenges through the stages of the N3XTCON project.

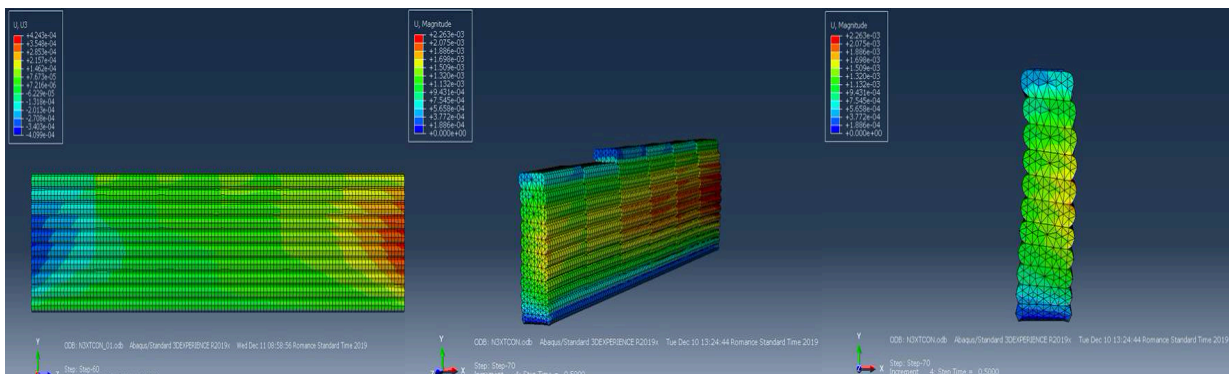


Figure 4.6: Printing simulation (Screenshots taken by DTU).

Research Institutions

The three research institutions involved in the study each have assigned a particular aspect of the project which best aligns with their research capabilities.

DTU. One of the primary focuses of DTU's research is directed towards early-age mechanical behaviors of the concrete. This consists of material modeling using programs to predict material behavior during the printing process. This process includes Digital Image Correlation (DIC) which determines the deformation during a print to correlate time with loading. DTU respondents state that a significant challenge with early-age modeling during DIC is that the

loading is changing at the same time the material is changing. Layers apply more load over time as well as the materials self-weight (DTU). These numerical models are validated against the DTI team who has the capacity to print these models.

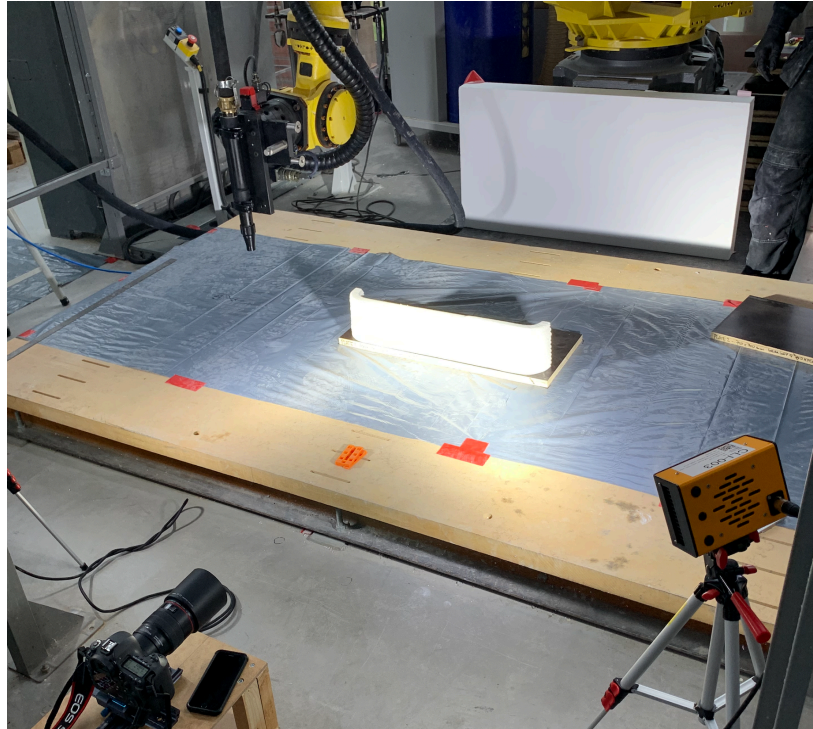


Figure 4.7: Digital Image Correlation (DIC) equipment configuration (Photo by author).

Another a challenge pursued by the DTU team is addressing the reinforcing issue. Perhaps the most apparent problem to development is the method in which tensile strength can be implemented into an extrusion process with such multi-dimensional freedom. **Currently, printing simple geometries have the capacity to include traditional reinforcing through printing the shell of the element and filling with traditional concrete. It is believed this method most closely aligns with existing placement methods accommodating the bi-dimensional aspects of vertical and horizontal rebar. The precast custom system is anticipated to be more challenging with non-standardized shapes and no clear direction on how tensile strength can be implemented by printing around bars or even what type of reinforcing will integrate with the printing process.** Although there are potential methods

being explored by other institutions, the N3XTCON team aims to do something not bound by present technology (DTU).



Figure 4.8: The concrete mould printed by WinSun (Wu et al., 2016).

DTI. The DTI team has the responsibility of numerical model validation as well as much of the responsibilities for project management. As DTI oversees the robotic arm printer used for the study, they are in charge of validating the models produced by the DTU team. Considerations involved with the physical printing of the material include many of the concerns stated in section (2.3.1.3) such as, print and set time, temperature, mix design, mix internal pressure and w/c ratio. Another prominent challenge confronting 3DCP growth is that of the printer's limitation to only print with aggregates smaller than 4mm, limiting the printing capacity to only mortars. However, researchers are optimistic in the material challenges

as they do not see them as problems not going to be solved (DTI). Rather the inclusion of reinforcing stands as a more immediate impediment to progressing in geometries and upscaling. Understanding these printing associations which govern the fresh and hardened states of the material is not only the goal of the research institutions but the overarching goal of the project in making the process more robust. This process entails the procedures outlined in section (2.3.1.3) of the literature review. As the parameters are not perfectly defined as to the implication on the final outcomes, breakthroughs across all aspects of the technology hopefully will improve the overall robustness of the process.

SDU. The SDU team's primary competency for the project is robotic programming for industrial processes. Their research activities consist of 3DCP user interaction, motion planning, and robotic methods for maintaining the print. The SDU team described the 3DCP as an up-scaled

gantry plastic printer. It utilizes a “Slicer” program which creates G-code which is sent to the printer to create the desired object.

A prominent challenge for the both the robotic arm, gantry and robotics industry as a whole is calibration. Calibration of the print head with its location in relation to the printed element is a significant concern, especially when stability is already in question. During a print, there may be interruption in the process such as a clogged head or mechanical collisions. The current code does not account for these disruptions. Thus, discontinuous prints must be achievable with minor implications. The robotic simulations are intended to control commands that aren’t dangerous to the print and also support the ease of operational use by command free motions. The ambition is to eventually have the process be as easy as that of a plastic printer (SDU).



Figure 4.9: Robotic Arm calibration at the Danish Technological Institute (Photo by author).

Architectural Designers & Structural Designers

Both the architectural and structural designers in the N3XTCON project have provided responses predominantly pertaining to the technology’s geometric and structural capabilities. Previously

reviewed in sections (2.4.3 and 2.4.4), these challenges align with the group's primary ambitions for the project's outcomes as well as processes currently underway to further 3DCP technologies growth. The responses from these groups on geometric and structural design appeared to overlap significantly in part to the material's traditional applications. Just as the design phase is essential to any construction project, significant consideration of aesthetic and reinforcing inclusion for structural integrity are the primary challenges for the design partners.



Figure 4.10: BauMinator (baumit.at/bauminator).

The designers are at a crossroads with this 3DCP technology. In one sense, the printer is capable to print free-formed structures, unbound by the simple geometries of circles and rectangles. The printer can be directed to print any geometry required without significant cost implications between a curved wall or a straight one, a twisted column or square one. Although not all geometries can be sweepingly addressed such as cantilevers, it is undeniably an attractive draw to this technology. On the other hand, the increased design freedom also becomes its greatest opponent to technological advancement. From every designer, and nearly all project partners, the issue of reinforcing bar inclusion to bolster structural applicability is the Achilles heel of progress. **It is said to be a giant obstacle as current codes are linked to modern geometries and fall into definitions of what are identified such as columns, walls, beams, etc. Although**

one ambition was to replace an entire structure and not concede to feature walls or columns. But even these have not yet been written into code on their capabilities because no one has been able to produce them reliably (HLA). Today, it is design by testing, creating a scale model until failure of the element. A second element is produced which undergoes additional testing before it is acceptable for use (DTI). Several designers stated an ambition for future research would lead the technology away from traditional reinforcing methods. One that is more accommodating to the freedom of design allowing 3DCP to live up to its fullest potential. The previously mentioned concern with printing of mortars versus concrete also creates new considerations if the tested processes will translate to applications previously proven successful with standard concrete and reinforcing. It remains to be seen if these dissimilarities between the mix design and rheology will prove too great a setback. Many questions are left for future inquiry. One strategy for the issue of structural integrity by one designer was the concession that it was hard to know or predict what standards will change. The technology needs an application to determine capacities and limits. It must adapt as the technology grows (BIG).

Suppliers

The supplier's role in the project entirely concerns the behavior of the cementitious material. Interview responses indicate that cement and admixtures are the essential components to produce favorable characteristics of the printed material. However, in order to align with one of the primary goals for the project, cement content must be optimized without compromising the other required capabilities of the printed element. Strategies for this direct much focus on the reduction of clinker during cement production and the inclusion of more supplements and admixtures for improved strength and set time (AP). The supplier also examines the effects of temperature/strength development of cement paste, compatibility with admixtures and other specialized testing of the material. They argue the future of cement is in the use of alternate materials like calcine clay and limestone for material optimization (AP). Reviewed in greater depth in section (2.2.5), material optimization links to many of the other challenges of the industry primarily, productivity and sustainability. By means of cost-efficiency of material use in order to be competitive in the market and through reductions in CO₂ emissions through waste reduction and material optimization.

Contractors

This response group is not currently active at this stage of the project. The structural design group double as contractors for this section.

Trade Professionals

The 3D concrete printing trade professional team from COBOD, has the project aim of producing a next generation concrete printer. Their expertise pertains to the print machinery and general field applicability of their technology. COBOD created the first 3D printed building in Europe, the “BOD”. While the trade professional team focuses on the deployment of a gantry style machine, the technical processes apply closely to both in the gantry and robotic arm methods of placement. Question N4 asks the trade professionals of the interchangeability of both



*Figure 4.11: A clip from a time-lapse by COBOD of their test “BOD” structure (cobod.com/videos).
Figure 4.12: The completed BOD structure in Nyhavn area of Copenhagen, Denmark (Photo by author).*

printer types and their responses were indicative of no clear divide in practices due to the early age of the technology, despite other partner’s observations of the placement system trends. **What was determined as potentially a greater deciding factor of printer type was the cost efficiency of its mobilization on-site.** The robotic arm requires 1-2 hours for calibration per print but has a reduced print area and may be relatively easier for smaller or single prints. While the gantry requires 8 hours for set up, or between 5-6 hours with mounting feet, which can print entire structures and only needs to be set up once. It boils down to set up time, reach and print time (COB). This distinction also leads to scalable applications. From section (2.4.5), we have seen gantry is typically able to print larger structures in situ as well as smaller ones off-site, and vice versa for the robotic arm with smaller prints. The COBOD team’s response on up-scaled

applications is that of optimism for an increase site-produced structures larger than what has been traditionally transported to the sites. Structures have been limited to 4-meter width due to transportation challenges which have otherwise been reduced to smaller modules to accommodate. Structures which are likely to see the greatest change include large concrete structures such as tanks, towers, chimneys, manholes, pipes and others alike (COB). These scalable applications and points of entry for 3DCP will be reviewed further in section (4.1.7).

Another unapparent barrier for 3DCP is that of greater industry technology level. The construction industry has only recently utilized 3D planning and design tools while on-site activities have been the same for some time. Many industries have a mindset for traditional methods with the expectation of new outcomes. 3D printers require a change in mindset for the process to be successful. Furthermore, for a technology which only reduces costs a marginal amount may not be worth the risk of adopting in addition to the prerequisite of changing the company infrastructure (COB).

Ambitions from trade professionals of a next generation printer might include several trade activities into the construction process to boost output. This would allow a greater portion of the project to be automated besides the structure, thus allowing greater cost efficiency. As the printer is solely capable of printing concrete, inclusions of other building trades create a vital point of entry into the market. An additional strategy might be to blend strengths of both printing styles to improve where the counterpart has found success. Improve axial freedom for the gantry system or modify the robotic arm's printable areas to create greater ranges. However, technical challenges from other aspects of the technology currently confront these ambitions. It may not be too far in the future to expect this hybrid to emerge as a strong competitor within the market sector.

Overall, from the partner groups, the most reoccurring challenges presented from the interviews on 3DCP systems and challenges were reinforcing strategies and sustainable processes. These two barriers feed into the overall obstruction being process robustness. Robustness is defined as the collective strength of all steps in the 3D concrete printing lifecycle. Lacking technology,

material variability, process optimization and many others amass to the grand endeavor that is furthering the development of 3D concrete printing technology.

4.1.6 On-site/Off-site Applications (7)

In this section, interviewee responses to questions pertaining to on-site applications will be addressed. The off-site/prefabrication prospectus has been reviewed in section (4.1.3) and one of the primary goals of this research is to examine the effects and implications of the on-site deployment of 3D concrete printing technology. Questions in this section primarily pertain to site interactions and printer safety through technical considerations of hypothesized situations when



Figure 4.13: 3D printed house by Total Kustom (totalkustom.com).

in use for on-site production. This section and the following strike at the heart of this study on implementation and acceptance of 3DCP technology. Questions asked in this section include N4, N5, S3, S7, S9 and S11. The primary respondents of this section include research institutions, trade professionals and architectural designers.

Site Interactions

The responses from the interviews tended to focus on the prospective application of a gantry style printer. From previous literature and interviews, it is trending to be the first printer deployed in the field. Responses from the COBOD professionals on its field operations was that

at the moment, the printer would require a kind of environmental protection. An enclosure of the printer would protect against extreme conditions that might affect the material and process (COB). The printer is, however, capable to work in the rain, but may require a tent. This creates the concern where wind might affect a tented area, like other tented work on-site (COB). Researchers compared the gantry system to that of a crane. Whatever is in place for a crane operation should be in place for a gantry printer as well (SDU). It is also believed that with the printer present on-site there would be less direct human interaction, larger structure limits, greater potential for machine-caused injury but improved productivity (DTI). Although at a smaller scale, similar safety hazards to those already present with a crane will require greater vigilance.

Safety

The safety considerations for 3D printers are numerous. The gantry and robotic arm printers can be treated as two very different equipment types for the same production process. For the context of a safety analysis, both printer styles can be visualized for on-site use despite industry tendencies. The responses of these printers' source from the COBOD team that outline safety features for their gantry printer and researchers with experience with industrial robots and robotic arm style machines.

Gantry. This style of printer is anticipated for use with larger structures, not easily transportable to the site. Thus, it requires a large area of operation. COBOD has numerous measures they recommend for use on-site. When in operation with workers around it, the printer head travels at 25centimeters per second. This is the speed in which the machine can be considered a "collaborative robot" in which it is "CE" marked safe for workers that may work alongside the printer. For more rapid operation, in which the print head may move between 1-1.5 meters per second, a safety fence and gate are required. The gate is engaged when in high-speed use and requires a multi-step process to increase the printer speed. Additionally, if the head meets resistance or collides with something, it automatically stops. However, when moving at high speeds this hazard is extremely dangerous or fatal (COB). Hazards anticipated to be associated with gantry operation would be struck-by or from above in material falling, similar to hazards associate with crane activities.

Implementation of safety measures for these printers are in-stride with the overall technology's development. Safety procedures and methods must be developed alongside as it is a totally new technology. With that, it is hard to determine where hazards may be located. There have not been dangerous situations. But it is hard to know exactly where they may be (COB). The inclusion of a camera or scanner inside the print are is being looked into as a redundant measure in addition to human operators (SDU).

Robotic Arm. Although projected for use predominantly off-site, many of the features discussed in the analysis can be applied to an on-site environment. Research institution involved in the N3XTCON project are using this style of printer for testing of materials in the early stage of the project. While external interactions are not the focus of their research, the robotic arm printer can yet provide valuable insight into prospective safety methods. The robotic arm printer can be compared to a mobile robot. It currently can operate safely within a fenced area. The arm moves relatively faster than a gantry but is still slow. The robotic arm is seen more commonly as a collaborative robot in its operation near workers. This creates more stringent regulation than normal crane activities. The safety hazards anticipated to be more common with robotic arm prints will likely be caught-between and struck-by due to the condensed workspace (SDU).

Apart from the direct safety measures involved in printer operations, the greater context of site safety may benefit through on-site use by means of reduced worker involvement.

Although predicted not to be implemented in the near future, the reduction in manpower required for work activities will reduce people on-site, thus reducing the hazard exposure (COB). This reduction includes the traditional hazards associated with concrete construction but also the long-term effects of repetitive or particularly laborious work. Discussed in the American contractor's perspective, site safety of robotics is a strong determinant of use. Section (4.2) will examine these opinions and provide greater insight as to the importance of safety and worker health in the presence of construction robotics.

4.1.7 Field Integration (8)

This section of the analysis will review the previously discussed technology performance

metrics. As covered in previous literature in (2.5.2), these metrics include but are not limited to cost, time, quality, safety and sustainability. Questions asked in this section include N5, S3, S5, S6 and S8. Other considerations from the partners will be reviewed in this section as well. While there are many internal and external consideration for technology adoption, for this analysis, the field deployment of 3DCP will be the context in which the technology will be inspected.

The industry issues discussed in section (2.2) align with desired outcomes of performance metrics in section (2.5.2). These metrics encompass the overarching themes of field integration



Figure 4.14: Dubai Municipality Administrative Building by Apis Cor (apis-cor.com).

throughout this analysis. For the sake of this analysis, field integration can be interpreted as industry integration. Although many other external factors exist when considering technology adoption, this study targets these metrics as they pertain specifically to the technology in question. The five metrics provide a basis in which similar technology can be assessed for its potential integration into the construction sector. Response on these metrics will be reviewed from COBOD trade professionals and research institutions. Additional themes presented in the interviews as factors for adoption, not previously mentioned in the five metrics will also be included.

Productivity

Interviewees expressed the major consideration for 3DCP industry adoption to be reductions in cost and time versus existing practices. Both improvements to cost and time equate to productivity and efficiency savings. Question S3 determined the greatest drivers and barriers to implementation and the most common response were improvements to productivity. Questions S6 and S8 ask researchers on the effects on material and labor for the relevant construction processes. Both of which are expected to decrease the requirement of non-value-adding activities and thus optimize the processes. Material and labor make up nearly the entirety of the construction cost. By altering these inputs, productivity will stand to gain the most. While the significance of productivity cannot be quantified, it stands with weight across literatures and interviews as the most prominent factor of 3DCP and innovation adoption.

Quality

While not unanimously considered to be as strong of a contributor to adoption as productivity, quality and output complexity was found as a notable factor for adoption. The challenge with quality at this stage is process robustness and the lack of reliable outputs.

Safety

Safety among the respondents was not considered to be a driver to technology adoption. Safety features and implications were discussed in the previous section but 3DCP is not widely considered to provide relief in the realm of worker safety health, despite its indirect benefits.

Sustainability

Sustainability was considered a strong factor of adoption. From nearly all the interviewees, sustainability was consistently mentioned as a significant driver and benefactor of adoption. Through the previously stated methods of material optimization and reduction in construction waste, 3DCP processes have the potential to replace, commonly considered archaic, and outdated methods of construction, thus, providing an eco-innovative alternative.

Other notable factors of consideration discussed by the interviewees which warrant further research as to their contribution to field integration include: integration through application by means of targeted niche markets which expand into greater space as the technology grows, increased design complexity demanded by projects driving adoption, industry input on material, design and structures can improve collaboration between lab and field for faster, more capable technology deployment.

4.2 USA Industry Perspective

In this section of the analysis, information was collected from interviewees through the author’s affiliation with the University of Washington and with general contractors in Seattle, Washington. The questions in the “I” group were developed for respondents without any affiliation with the N3XTCON project. Some questions pertain to 3D concrete printing primarily as a means for comparison against existing practices used in the industry today. The question areas which were reviewed in this group are shown in *Table 4.3: Industry Interview Question Areas*. Topics pertaining to 3DCP to on-site application and automated processes are included as well. The purpose of this section is to not only provide a contractor’s perspective but a comparative section of American views of construction automation and technology adoption experiences. Within these contractors’ responses, the topical themes present throughout this study will be examined individually and later discussed in the following section against the larger analysis of findings in section (4.3). Their breadth of experience stretches from the office to the field and among them are various instances in which new technologies of their time were introduced to them.

Table 4.3: Industry Interview Question Areas

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|----------------------------|-------------------------------|---------------------|-----------------|--------------|-----------------|--------------------------------|-------------------|
| N3XTCON Project Management | Respondents Field Application | Competing Practices | Industry Issues | 3DCP Systems | 3DCP Challenges | On-site/ Off-site Applications | Field Integration |
| | √ | √ | | √ | | | √ |

Respondents Field Application

Questions I1-I4 asked about the interviewees experiences and perspectives with accepting new technologies being as their positions' allowed them to make these adoption choices for their team. Two of the interviewees came from the field and office backgrounds. In the office context, instances of software adoption to streamline management procedures was common, which might eliminate the need for an additional Project Engineer (HSW). This can also be said for management techniques and tools introduced to contractors involved in the project management profession. In the field context, superintendents are frequently introduced to new technology through salesmen. Tools and equipment being the majority of new technology being exposed to the field. Efficiency, safety and time savings are presented as the major considerations (HSW). However, in the field environment, the workers must now be factored into the equation as opposed to the office staff which may be company employees. While similar ideology for comparison exist between office and field, we can also examine the factors which drive assessments across related construction manufacturing and production processes.

Competing Practices

Questions I6-I10 inquire about the interviewee's opinions on alternate practices and advanced methods of construction. One of the interviewees has extensive experience with digital construction techniques including CNC customization, laser cutting and with 3D printing of plastics. Their work involves numerous fabrication techniques, most of which rely heavily on digitalization and models. 3D printing is one of those technique currently being used by the respondent. When asked about existing methods versus the future of 3DCP, the outlook is somewhat optimistic. In the right context, it may prove valuable. However, precast concrete is the greatest competitor of printed concrete which is a sector that is dialed in, straightforward and profitable (TC). Other points of discussion include construction robotics. Responses to the future of field robotics were expressed to have great potential and explode onto the scene, first off-site and manufactured then assembled on-site. It was considered to have a huge unlimited potential in the future of construction (TC). 3DCP is only one specific application of construction automation, and as the robotic technology evolves, so too does the broader field it which it aims to integrate with.

Field Integration

Similar to the N3XTCON project, cost and time savings remain the utmost consideration for new technology adoption. **Responses align on this very uniformly concurring that efficiency and time savings are key and that a proven tool is easier to implement than an unproven tool. This is typical in construction and must be proven in the field to work (HSW).** The introduction of new tools involves a learning curve. This is necessary for weighting the long-term versus short term sacrifices of efficiency and labor time.

Safety is also seen as the prominent factor for adoption, granted it does not further endanger workers for the sake of productivity. Any application regarding safety and not putting lives at risk is a good application. This could include confined spaces, abatement, welding, electrical wiring, etc. (HSW). **Safety can be seen as an inroad of adoption by convincing the field that they will have a healthy workforce and better way of life using the robots. This is not necessarily a replacement but can simply assist in unsafe tasks to make work easier, safer or better.** Use a robot instead of human whenever there is a safety question (HSW).

The largest challenge to field acceptance aside from cost is labor objections and job replacement resentment. **Affirmed by all three contractors, the acceptance of the labor force is seen to be a big obstacle out of fear of losing their job. Workers have demonstrated possessive attitudes of work and even aggressive resentment (TC).** It is also expected the increase in field robotics will be met with resistance by the labor unions (HSW). Prior to the use of site robotics is the current practice of digital fabrication and having component of the work completed by machines has been historically met with resistance.

From the interviews with the American contractors it would appear from the list of reviewed technical performance metrics that sustainability does not hold the same value to the contractors as to the rest of the project players. While attributes of digital fabrication technology provide similar benefits, environmental sustainability and waste reduction was not discussed as a driver of adoption. Although this portion of the analysis is in the USA industry perspective, opinions of the contractor may not align with those in Denmark. Architect, engineers, suppliers and other

construction professionals were not interviewed in the USA and cannot accurately provide a solid ground for a comparative analysis.

4.3 Discussion

The N3XTCON project is in a noble pursuit of furthering a potentially game changing technology. The project directs its focus to select areas of development with the hopes to bring about the next generation of printers to spring the practice into a new era of construction. The previous analysis sections reviewed project partner's responses to a variety of topics significant to the building and design industry. The prominent topics are extracted from previous literatures and organized into interview question areas which will be used to open a discussion of the partner's responses. Discussions are built on data collected from this project and its status at the time of the study. Outcomes drawn from this study are used to extrapolate areas of further research while considering the limitations.

Precast Industry – Competitor or Collaborator

One of the greatest challenges for 3DCP adoption is the existing precast industry. It is apparent from interviews and literature that the current methods of casting structural elements are cost efficient and reliable. Unfortunately, the same cannot be said about 3DCP. Traditional structural geometries provide predictable building components, albeit repetitive in nature. It is likely the only point of entry for 3D printed elements into current construction methods to be in highly personalized, non-structural feature elements, those that would be unrealistic to produce with traditional methods. At this stage in technology development, the same would hold true for on-site as well as off-site printing from lack of processes robustness. As stated by the architectural designers, the ambition would be to transcend feature elements into larger portions. The precast industry is in competition with the 3DCP industry due to their encroachment of some of their market. Thus, this becomes an opportunity for the technology to become integrated into mainstream practice. The futures of 3DCP and concrete companies realize the value in the custom and housing applications as some of the first to adopt this technology. It is uncertain as to which function will be utilized first as numerous test projects have sprung up across the globe in both custom and housing applications. Both methods have their issues but it is clear to see with so much collaboration and current success that the practice will continue to develop across a

range of fields. In 2018, PERI group, a leading manufacturer of formworks and scaffolds, invested in a minority stake of COBOD (COBOD, 2018). This can be seen as a big win for 3DCP companies with the competition accepting the shifting of practices that is becoming more and more common among start-ups and established players. However, 3DCP as a competitor for stand-alone precast products is unlikely in the near future.

Productivity and Sustainability – Now and Then

Expectations for 3DCP's ability to ease the pressure of many widespread industry issues are high, almost unreasonable. The foremost being productivity. This doubt can be attributed to the partner opinions on mono-task printing and lack of cost-competitiveness. 3DCP at this phase is almost sufficient at producing mortar structures. The next step will be concrete. However, in order to surpass existing methods of construction, new practices must become more efficient and superior to the old. Thus, without the inclusion of multiple automated building trades, costs will not be reduced to a point for adoption. Furthermore, the existing printing process is not competitive enough to stand up to simple structural elements, let alone entire houses. While the process is anticipated to reduce material and labor time in the long run, its actual impacts on industry productivity may be negligible without more process robustness and trade activity optimization.

Sustainability is also a strong driver for development. The partners indicated as much through the reoccurrence of the theme. As discovered in interviews and literature, 3DCP while it has the potential to permit less CO₂ emission, the reduction may be minor due to the increased cement dependence and redistribution of emission among materials and the overall lifecycle. One of the inherent benefits of 3D printing is the absence of formwork, thereby reducing non-value adding materials and labor. However, this requires greater stability of the print, currently, most readily achieved by increases in cement or admixtures. Life cycle analyses of the process are underway, but without substantial reductions in CO₂ emission in concrete materials, 3DCP will likely not contribute to global relief as much as optimistically anticipated.

It is apparent from the interviews that industry professionals are likely to focus on marketability and production. While researchers and designers may tend towards sustainable outputs and

processes. In the end, construction is a business. In order for the practice to take hold, the process must make strides in reducing operating costs. None of the other factors of integration matter without cost efficiency.

3DCP – The Path Ahead

With a wide range of technical aspects and challenges for 3DCP technology, it is difficult to define one path to venture down. The N3XTCON partners all have various goals in mind for the project and all encounter various challenges. The single most prominent as defined by the partners is that of lacking process robustness. This encompasses all steps of the 3DCP process and branches off into numerous technical issues for consideration. The two found to be most common from the interviews was the previously mentioned material sustainability and also reinforcing challenge. Integration of reinforcement is not a challenge unique to N3XTCON. Between the functions of on and off-site, the simple geometries are expected to be reliably produced in the field first due to their inclusion of traditional reinforcing. With custom printing, geometries are highly variable and thus standard reinforcing will be costly to replicate. This, however, is not an issue if used in a non-structural application, which is where 3DCP of custom elements has seen success. It is likely the application will continue in this manner until a ubiquitous reinforcing method is determined and regulators establish how these unique structures are code compliant.

Where there was previously expected to be a divide between on-site and off-site via printer type, it is further complicated by mobilization cost efficiency. An exception to this trend is companies like Apis Cor, which uses a radial arm printer on-site to print large-scale structures. The number of mobilization and calibrations for field printing is found to create another point of attention which may pave the way for hybrid printer types. Innovative placement methods beyond the two primary systems of gantry and robotic arm placement are being investigated by other European institutions such as ETH Zurich dfab, in the hopes to find its entry into a niche market. By creating variance in methods, the technology has improved opportunities for overall industry integration. This may however broaden the technical challenges as the innovations expand into uncharted territories.

Is Safety Still First?

Printer safety must keep pace with technology's overall development. There is lacking literature on 3DCP technology from the safety and health perspective due to printer's continual developments. As it is an evolving technology, the hazards may not be readily anticipated. Members of the COBOD team emphasize the importance of safety in these early stages due to the lack of foresight in the final product. Despite the safety measures in place around the systems currently, it is possible that in order for the technology to advance, safety may take a backseat to innovation. The USA contractors determined while safety is an important factor for integration, if the technology is not safe enough to work alongside, it will not be introduced. Although not explicitly stated in the interviews, if there is a reduction in cost but a sacrifice in safety, the technology will not be integrated no matter the savings. This can be expected across all general contractors managing site operations with any awareness of a safety culture. Therefore, without the N3XTCON project's primary focus being safety but rather innovation or merely cost efficiency, the projected end users of the technology may reject or accept reluctantly the printers if ample measures are not included. The team is however directing deserving attention on this topic and has taken steps to ensure standards are met.

Impacts for Integration - Cost is King

Cost and time savings remain the sturdiest factor for integration. This held true through the literature as a motivator as well as barrier. Reductions in cost and labor propel R&D in concrete printing towards the field every day. It was determined by both USA and Danish interviewees that efficiency and time savings dictate field implementation. The Danish respondents then placed sustainability as another strong factor while USA contractors placed safety as their next consideration. This is not to infer upon the Danish safety culture but rather raise the question upon the project and its omission as a specific aim. Safety and sustainability are two prominent industry issues and performance metrics discussed in detail throughout this thesis. However, it is not a comparative study examining these values in depth, rather through the lenses of 3DCP adoption. Differences between country values is also a likely contributor to the evaluation of integration factors. While cost is intuitive as a pillar of business, sustainability and labor

acceptance are more difficult to assess without a balanced comparison. This however cannot be confirmed due to the absence of Danish contractors, only speculated.

Challenges to field integration and overall technology development was determined to be lacking robustness. The N3XTCON project distinguished this to be the foremost concern in all aspects of 3DCP development and integration. American contractors declared that a challenge to general construction robotics and automation would be labor acceptance. Fear of job loss has raised questions in all industries, not just construction. But for construction specifically, as such a high-risk occupation, the fear should not be as profound as expected with innovations directed towards improving safety and making work easier. When asked about COBOD's famous "BOD" print, workers revealed positive reactions to the automated process with similar ideologies in Scandinavian countries (COB).

It should be mentioned that the partners in the N3XTCON project will primarily not be the end users of the technology. Workers in the field will operate these machines and may have different perspectives on best practices and applications. Thus, while partners tend to value the prospective benefits of material savings, contractors may value the potential for hazard mitigation. The N3XTCON project is currently taking into account these varied perspectives through their multi-disciplinary team. Industry input is likely a significant proponent of adoption in order to bridge the divide between the lab and field. While this was previously found in literature, the studies which examine technical aspects of 3DCP technology need further to be explored as to the significance of performance metrics in specific factors of integration.

The N3XTCON Case Example

The N3XTCON study has provided numerous benefits beyond those which might be attained in a quantitative study of 3DCP research. The research process and its prospective outcomes have permitted first-hand interviewees and ideas from those with powerful knowledge about this technology, previously confined by numerical data and concentrated experiments. However, the research aims for this thesis and the N3XTCON project do not align seamlessly. The on-site integration aspect of 3DCP is far in the future with many other pressing obstacles confronting it now. Thus, the responses by many of the interviewees have been speculative as to the precise

factors influencing its on-site deployment. This was somewhat expected as an emerging field that site-interactions would be difficult to foresee as an ever-changing environment. The method can be summarized as a general approach as the study progressed due to the variability in responses which broadened the scope beyond the on-site aspect of the research. As an emerging field, the hypothesis of on-site integration devolved into “industry,” meaning general use in the building/design field as a result. While many of the research questions were answered in this study, personalized attributes unique to 3DCP integration were not completely distinguished at this stage in development and only speculative in nature.

Reflection

As with the nature of case studies, universal conclusions cannot be drawn from one example. The level of technological development is not sufficient to make such claims, nor would it be acceptable to say with certainty of the definitive direction of growth in any application. This exploratory study considers the technological aspects of 3DCP important for integration. There are potentially many external factors from the adopting organization, government and other entities which may impact a willingness to adopt technology. These are not the focus of this study but should be explored in the context of 3DCP as breakthroughs ensue. Another limitation was in the technology’s developing status as it will continue to mature in the coming years. This study provides a snapshot in time of one particular project. There are numerous projects across the globe with different interests and goals for similar innovations. Thus, integration factors may differ across time, just as the parallel techniques for 3D printing and digital fabrication may differ. In the comparison of USA and Danish perspectives, no Danish contractors were able to be interviewed to compare against USA contractors’ perceptions. However, this was not intended to be a comparative study. It only seeks to examine 3DCP technology developments, trends and outlooks for on-site integration from those available to be interviewed at the time.

Chapter 5. Conclusion

This section will summarize the main questions guiding the research and their corresponding results. The main findings will be explained and as well as their significance to the construction industry and the field of 3D concrete printing. Conclusions will be guided from previous literature and interviews during this study. Finally, author recommendations and suggestions for future research will be discussed to empower the realm of inquiry into 3DCP development.

5.1 Summary of Findings

The aims of this research were to examine contributing factors, developmental strategies and outcomes of 3D concrete printing on-site integration and their significance for the building and design industry. Findings from interviews of the 19 researchers, designers, contractors, trade professionals and managers were gathered and analyzed. Results surrounding the on-site readiness and application of 3D concrete printing technology is making promising strides but cannot be certain of complete industry integration at this stage in development.

Table 5.1: Summary of Findings

| Area Notation | Interview Question Areas | Key Findings |
|---------------|---|---|
| (1)(2) | N3XTCON Project & Respondents Field Application | <p>The N3XTCON project holds a multidisciplinary approach that contributes to the advancement of various 3DCP features through partner competencies.</p> <p>The architectural and structural designers strive for design freedom starting with unique building elements as supplemental components with the ambition to progressively implement larger structural presence into projects.</p> <p>The research institutions, contractors and suppliers mostly agreed that advancements in 3DCP would not necessarily revolutionize their respective field or the building industry as a whole. Rather, be used as a supplemental tool to allow for new construction methods but not as a stand-alone practice.</p> |
| (3) | Competing Practices | The gantry and robotic arm printers are two styles of production have emerged as two distinct methods of 3DCP expected to propel the |

| | | |
|--------|--------------------------------|---|
| | | <p>industry forward. Both printers are expected to compete in structural and architectural precast settings but are far from optimized.</p> <p>It is anticipated that the Danish market would likely not be the recipient of 3DCP housing but rather the customizable components would serve as a supplemental option for the demand of unique features. The direction of similar industrialized countries may be apparent as the 3DCP industry trends towards highly customized, complex structures.</p> |
| (4) | Industry Issues | <p>Productivity: For large-scale on-site printing, there were concerns for proficiency in two areas: 1. The inability to be cost efficient by only completing one construction activity and 2. Material use and placement processes are not optimized to be competitive.</p> <p>Labor/Skills Shortage: Partners believed 3DCP would not lead to a complete job loss, rather a shift in skills allowing work to be completed using less labor requiring improved technical competence.</p> <p>Worker Safety & Health: Expected to provide the indirect benefit of reduced manpower and decreased hourly exposure to risky work.</p> <p>Housing Shortage: Partner responses determined the large-scale printing of housing is expected to be utilized before smaller custom prints and across different global regions.</p> <p>Sustainability: The absence of formwork creates the increased dependency of material performance forcing cement content to be sizably increased for structural integrity. Increased cement results in a larger CO2 footprint and the dilemma of improved material optimization at the cost of emission.</p> |
| (5)(6) | 3DCP Systems & 3DCP Challenges | <p>Reinforcing strategies are one of the most pronounced challenges which stems from the unlimited design potential. Development of a ubiquitous reinforcing method has forced a crossroads between design opportunity and proven strategies.</p> |

| | | |
|-------|-------------------------------|--|
| | | <p>Interviewees determined conformation to existing building codes to be a significant obstacle. Codes designed specifically for printed structures are challenging due to unlimited design possibilities. However, with the overall processes faltering replicability, codes cannot be written on 3DCP capabilities in any application because the industry has been unable to produce structures reliably.</p> <p>Site mobilization may become a significant factor in cost efficiency when deciding the printer type.</p> |
| (7) | On-Site/Off-Site Applications | <p>3DCP safety measures are in development alongside overall process robustness. Procedures must be developed in conjunction with other aspects of the innovation due to the nascency of processes. As a result, this creates difficulty in anticipating potential hazards. Deployment of 3DCP in the field reduces required manpower and thus the total hours of exposure to hazards.</p> |
| (8) | Field Integration | <p>N3XTCON interviewees determined productivity and sustainability to be the most important factors to adoption.</p> <p>Lacking robustness and ongoing technological improvements were found to be a significant barrier to adoption.</p> |
| (4.2) | USA Perspective | <p>USA contractors determined productivity and worker safety to be the most important factors to adoption as one may not succeed without consideration of the other.</p> <p>Field labor resistance of new technology was found to be a significant barrier to adoption.</p> <p>Worker safety can also be seen as a potential avenue into the industry.</p> |

Contributing factors to integration were determined early in the literature review process as sweeping considerations without distinction to this technology in particular. While there include external, internal, governmental, organizational and many more factors determined in section (2.5.1), this study examined the performance metrics associated primarily with the adoption of a technology. More specifically, the on-site perspective of influencing factors was mentioned as an afterthought by N3XTCON partners rather than a distinguishing dynamic. From the

developmental standpoint of the partners, steps taken towards integration currently revolved around the overall functionality of the processes as a whole. Hypothesized field integration aspects resulted in fairly short-term responses primarily due to the challenges of the here-and-now. When examining the long-term outcomes and applications of 3DCP, there emerged numerous benefits and plentiful applications. The literature examined several applications by means of productivity, labor/skills shortage, worker safety, housing shortage and sustainability. The N3XTCON team overall saw sustainability and productivity as two of the most prominent outcomes of this research. The reduction in material usage and non-value-adding labor were seen to not only optimize costs but CO2 emissions. Additionally, through large-scale printing, the possibility of relief to the global housing shortage as well as constructability issues with oversized prefabricated concrete elements is a powerful motivator. Improved design opportunities through multi-axial freedom and advanced mixtures for unique structures also was a powerful draw to success. The integration of custom designs and structural components are not without competition however. The existing prefab industry is strong and established. 3DCP is young and inexperienced. It will be difficult for 3DCP start-up companies to gain a foothold with such a prominent adversary. Yet the practice is gaining ground among some major concrete players. It can be seen as a niche technology with its highly customizable capabilities ideal for applications traditionally not feasible for current methods of casting or even CNC customization. This may provide a point of entry for the printing companies to find a new market to section or may be an opportunity to join forces with established entities. One of the reiterated strengths of the N3XTCON project was its collaborative approach and inclusivity of industry partners. This included precast manufacturers, 3DCP trade professionals and many more. All levels of the process lifecycle offered input at all stages of development intended to improve transparency and smooth the lab to field transition. However, it was not determined that field labor was included in the project decision-making, a crucial standpoint in end-user interaction. Perspectives from USA contractors raised essential concerns as to the safety of automation on-site as well as the inevitability of transitions in labor. Where N3XTCON partners displayed much consideration for sustainability and technology development as factors for integration, USA contractors redirected attention to the importance of field workers. Safety and site interactions are difficult to predict as many unforeseeable hazards may arise within the ever-changing environment. This also creates more uneasiness among workers with the fear of job replacement from evolving practices. These

predictions cannot be readily accounted for with both the current and long-term obstacles to integration not fully comprehended. In all, the results of this study have provided a foundation for future research into the applicability of on-site deployment of 3D concrete printing. Integration is process that with time, will provide fruitful outcomes and open new realms of discovery.

5.2 Study Contributions

The purpose of this study was to provide an analysis of the development and applicability of 3D concrete printing for on-site applications. In the process, the literature review established the state-of-the-industry in which the technology stands in addition to the intended trajectories stakeholders aim to propel the industry. What distinguished this thesis from other works is twofold: 1. The 3rd party perspective of the author upon a European research project which aims to advance this technology and 2. The qualitative approach to data collection of an emerging technology via interviews. While there are numerous ongoing 3D printing research project utilizing varieties of materials and processes, this study includes an additional layer of project management into the study where other endeavors have not. The N3XTCON project serves as not only an example of the technology in question but the processes in which innovative technologies endure towards industrial acceptance. The interview process also played a significant role in contributing to new methods of discovery. Some entities involved in the project were pulled from a field of highly technical, highly numerical disciplines. This thesis is conducted through the department of Construction Management, which historically has leaned towards a qualitative approach of human, natural and social sciences. By incorporating an observational aspect into a technical project, data collected in an external analysis provided a wide series of results between both quantitative and qualitative realms. Further contributions can be observed at this early stage in the context of prospective benefits of industry issues. The table below identifies these via the five outstanding issues.

Table 5.2: Industry Contributions

| Industry Issues | Contributions |
|--|---|
| Productivity | Provide new insights to the field of digital fabrication and boosts to productivity via automated, streamlined processes. |
| Labor/Skills Shortage | Stabilize the labor/skills shortage of the industry via an improvement in required competencies to modern construction practices. |
| Worker Safety & Health | Reduce worker count on-site thus reducing overall hours of exposure to potential hazards. |
| Housing Shortage | Allow the opportunity of efficient, replicable, inexpensive housing options to satiate the global housing shortage. |
| Sustainability | Drive modernized construction techniques to greater awareness of environmental considerations. |
| <p>Note: Industry issues are also reviewed in depth in section (2.2) and via Technical Performance Metrics of field integration in sections (2.5.2) and (4.1.7).</p> | |

The findings of this research are not intended to affirm or refute any existing theories in the field of 3DCP. It rather proposes to explore the field of innovation to provide a general direction through the lens of an in-progress study. It expounds upon ideas for consideration as the processes matures. On-site and general industry integration is the eventual end goal of this endeavor, as stated by the N3XTCON team. The results merely bring awareness to the long-term goal that is field adoption when so much attention is allowed to the challenges of now.

5.3 Future Research

The conclusions drawn from thesis can be applied across a wide field of stakeholders in the building and design industry. Therefore, the study was limited to broad generalizations of trends of development and adoption in 3DCP technology. The field has a wide expanse of unknown territory free for discovery.

From the findings, further qualitative studies utilizing case studies can be conducted as every research project is different, enabling new perspectives and insight. This research is also free to explore implementation as well as other facets of the technology due to its nascency. But to

better understand integration, research should be conducted upon a significant discovery altering the technology's applicability or adoptability. At this stage, developments are technical and concerned with the robustness of the current processes. But for long-term success, these goals for integration should be explored in depth during the early stages for improved adaptability to on-site applications. Similarly, there are numerous theories of construction technology integration. As 3DCP develops, it should be examined against current adoption models to align or branch off established works.

Another point of improvement for the study should be by way of surveying and interviewing field workers and general contractors for their input on 3DCP as the end users. One of the ambitions of this project is to one day make the concrete printing process as simple as the operation of a plastic printer. In order for that to occur, standpoints from those who will be operating and working alongside these machines will need to be involved in the assessment process.

A final recommendation of further research may be through the execution of a comparative study from multiple countries which would be helpful to determine values of integration research on 3DCP technology across global regions. This study may be useful in targeting specific markets interested in the introduction of this technology through specific avenues of implementation. This would build upon the comparative section in this thesis between the USA and Danish perspectives of integration values. Furthermore, comparing entities of equitable positioning within organizations is also crucial for a reliable comparison. Contractors to contractors, designers to designers, while only varying country of origin.

Chapter 6. Bibliography

- Bock, Thomas. "The future of construction automation: Technological disruption and the upcoming ubiquity of robotics". *Automation in Construction*, Volume 59, (2015), Pages 113-121, DOI: 10.1016/j.autcon.2015.07.022
- Bock, Thomas & Linner, Thomas. "Site Automation: Automated/ Robotic On-site Factories" Cambridge University Press/ *The Cambridge Handbooks in Construction Robotics*, (2016), DOI: 10.1017/CBO9781139872027.
- Bos, Freek; Wolfs, Rob; Ahmed, Zeeshan; Salet, Theo. "Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing". *Virtual and Physical Prototyping*, Volume 11:3, (2016), Pages 209-225, DOI: 10.1080/17452759.2016.1209867
- Buswell, R.A.; Leal da Silva, W.R.; Jones, S.Z.; Dirrenberger, J. "3D printing using concrete extrusion: A roadmap for research". *Cement and Concrete Research*, Volume 112, (2018), Pages 37-49, ISSN 0008-8846, DOI: 10.1016/j.cemconres.2018.05.006
- Butt, Jared. "Construction Workers Divided on Safety of Robots". (4/11/2019). URL: <https://myosh.com/blog/2019/04/11/construction-workers-divided-on-safety-of-robots/> (Accessed 5/24/19)
- Chieochan, Oran; Lindley, D; and Dunn, T. "Factors Affecting the Use of Information Technology in Thai Agricultural Cooperatives: A Work in Progress". *Journal of Information Systems in Developing Countries*, Volume 2:1, (2000), Pages. 1-15. DOI: 10.1002/j.1681-4835.2000.tb00008.x.
- COBOD International A/S. "German PERI Group acquires significant stake in Danish COBOD International". (October 30, 2018). URL: <https://cobod.com/wp-content/uploads/2018/10/Press-Release-Peri-acquires-minority-stake-in-3D-construction-printing-company-COBOD.pdf>. (Accessed 3/5/20)

- COBOD International A/S. “Gantry versus robotic arm based 3D construction printers”. URL: <https://cobod.com/gantry-versus-robotic-arm-systems/> (Accessed 8/13/2019)
- Enshassi, Adnan; Mohamed, Sherif; Abushaban, Saleh. “Factors Affecting the Performance of Construction Projects in the Gaza Strip”. *Journal of Civil Engineering and Management*, Volume 15:3, (2009), Pages 269-280. DOI: 10.3846/1392-3730.2009.15.269-280.
- Forming America. “Concrete Formwork – Conventional vs. Engineered”. (8/17/16). URL: <https://www.formingamerica.com/concrete-formwork-conventional-vs-engineered/> (Accessed 11/12/19)
- Gambatese, John A. & Hallowell, Matthew. “Factors that influence the development and diffusion of technical innovations in the construction industry”. *Construction Management and Economics*, Volume 29:5, Pages 507-517, (2011), DOI: 10.1080/01446193.2011.570355
- Ghaffar, Seyed Hamidreza; Corker, Jorge; Fan, Mizi. “Additive manufacturing technology and its implementation in construction as an eco-innovative solution”. *Automation in Construction*, Volume 93. (2018), Pages 1-11, DOI: 10.1016/j.autcon.2018.05.005
- Jones, Kendall. “4 Major Challenges Facing the Construction Industry”. (2/8/2018). URL: <https://www.constructconnect.com/blog/4-major-challenges-facing-the-construction-industry> (Accessed 10/31/19)
- Leal da Silva, W.R. “3D Concrete Printing - from material design to extrusion”. [Presentation Slides] Retrieved from Danish Technological Institute website: <https://www.dti.dk/projects/3d-printed-buildings/36993> (2017)
- MarketsandMarkets. “3D Printing Construction Market by Material Type (Concrete, Metal, Composite), Construction Method (Extrusion, Powder Bonding), End-User Sector (Building, Infrastructure), Region (North America, Europe, APAC, ROW) – Global Forecast to 2024”.

(August 2019). URL: <https://www.marketsandmarkets.com/Market-Reports/3d-printing-construction-market-84104178.html> (Accessed 3/11/20)

McKinsey & Company. “Reinventing Construction: A Route To Higher Productivity”. (2017). URL: <https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/reinventing-construction-through-a-productivity-revolution> (Accessed 11/21/2019)

Nadarajah, Nithesh. “Development of concrete 3D printing”. Master’s Thesis. Aalto University. (2018)

PERI Group. “CNC Cutting and Formwork Assembly”. URL: <https://www.peri.com/en/products/services/cnc-cutting-and-formwork-assembly.html#q=cnc> (Accessed 2/14/20)

Pheng, Low Sui; Arain, Faisal; Mingdong, Tang. “Adopting Game-Changing Technology for Construction Productivity: A Pilot Study”. *International Journal of Construction Project Management*, Volume 11:1, (2019), ISSN 1944-1436

Reizen, Richard. “Issues Facing the Construction Industry in 2019”. (12/19/2018). URL: <http://www.gouldratner.com/publication/issues-facing-the-construction-industry-in-2019?A=SearchResult&SearchID=12264498&ObjectID=5464578&ObjectType=35> (Accessed 10/31/19)

Salet, Theo; Bos, Freek; Wolfs, Rob; Ahmed, Zeeshan. “3D concrete printing – a structural engineering perspective”. High Tech Concrete: where technology and engineering meet: Proceedings of the 2017 fib Symposium, held in Maastricht, The Netherlands, June 12–14, 2017. Pages xliii-lvii, Cham: Springer International, (2018), DOI: 10.1007/978-3-319-59471-

2

The Boston Consulting Group. “Will 3D Printing Remodel the Construction Industry”. (January 2018). URL: <https://www.bcg.com/publications/2018/will-3d-printing-remodel-construction-industry.aspx> (Accessed 11/4/2019)

Wangler, T; Lloret, E; Reiter, L; Hack, N; Gramazio, F; Kohler, M; Bernhard, M; Dillenburger, B; Buchli, J; Roussel, N; Flatt, R. “Digital Concrete: Opportunities and Challenges” *RILEM Technical Letters*, Volume 1, (2016), Pages 67-75. DOI: 10.21809/rilemtechlett.2016.16.

Woetzel, Jonathan; Ram, Sangeeth; Peloquin, Shannon; Limam, Mourad; Mischke, Jan. “Global housing stock has not expanded quickly enough to keep up with a surge in demand, but cities can focus on three supply- side solutions to make progress”. (October 2017). URL: <https://www.mckinsey.com/featured-insights/future-of-cities/housing-affordability-a-supply-side-tool-kit-for-cities> (Accessed 11/4/19)

Wolfs, Rob. “3D printing of concrete structures”. Master’s Thesis. Eindhoven University of Technology (2015)

Wolfs, Rob; Bos, Freek; Salet, Theo. “Early age mechanical behaviour of 3D printed concrete: Numerical modelling and experimental testing”. *Cement and Concrete Research*, Volume 106, (2018), Pages 103-116, ISSN 0008-8846

World Green Building Council. “Global Status Report 2017”. (2017). URL: <https://www.worldgbc.org/news-media/worldgbc-annual-report-201718> (Accessed 11/5/19)

Wu, Peng; Wang, Jun; Wang, Xiangyu. “A critical review of the use of 3-D printing in the construction industry”. *Automation in Construction*, Volume 68. (2016), Pages 21-31, DOI: 10.1016/j.autocon.2016.04.005

Zhang, Wenguang; Guan, Xiaoyu; Zhou, Xueqin; Lu, Ji. “The effect of career adaptability on career planning in reaction to automation technology”. *Career Development International*, Volume 24:2, (2019), DOI:10.1108/CDI-05-2018-0135